

EVALUATION OF TWO CLEANING METHODS  
FOR REMOVAL OF ASBESTOS FIBERS FROM CARPET

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## FOREWORD

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The Risk Reduction Engineering Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

This report provides information on the decontamination effectiveness of dry-vacuuming and wet cleaning to remove asbestos fibers from carpet under experimental conditions. A reduction in the amount of asbestos in the carpet would suggest a possible reduction in the potential exposure to building occupants.

E. Timothy Oppelt, Director  
Risk Reduction Engineering Laboratory

## ABSTRACT

The effectiveness of dry-vacuuming and wet-cleaning for the removal of asbestos fibers from carpet was examined and the potential for fiber re-entrainment during carpet cleaning activities was evaluated. Routine carpet cleaning operations were simulated by using high-efficiency particulate air (HEPA) filtered dry vacuum cleaners and HEPA-filtered hot-water extraction cleaners on carpet artificially contaminated with asbestos fibers. Overall, wet-cleaning with a hot-water extraction cleaner reduced the level of asbestos contamination in the carpet by approximately 70 percent. There was no significant evidence of either an increase or a decrease in carpet asbestos concentration after dry-vacuuming. The level of asbestos contamination had no significant effect on the difference between the asbestos concentrations before and after cleaning. Airborne asbestos concentrations were two to four times greater during than before the carpet cleaning activities. Neither the level of asbestos contamination in the carpet nor the type of cleaning method used greatly affected the difference between the airborne asbestos concentration before and during cleaning.

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## SECTION 1

### INTRODUCTION

#### BACKGROUND

Buildings that contain friable asbestos-containing materials (ACM) may present unique exposure problems for custodial workers. Under certain conditions, asbestos fibers can be released from fireproofing, acoustical plaster, and other surfacing material. The episodic release of asbestos fibers from aging and deteriorating ACM relates to a myriad of factors, such as the condition and amount of asbestos present, the accessibility of the material, activity within the area, vibration, temperature, humidity, airflow, use patterns, etc. A major concern is the extent to which carpet and furnishings may be serving as reservoirs of asbestos fibers and what happens to these fibers during normal custodial cleaning operations.

The Asbestos Hazard Emergency Response Act (AHERA) requires that all carpeting in areas of school buildings in which asbestos-containing materials are present be cleaned with either a high-efficiency particulate air (HEPA)-filtered vacuum cleaner or a hot-water extraction cleaner ("steam cleaner"). Little quantitative information is available on how effectively these cleaners remove asbestos fibers from carpet or on the potential for airborne asbestos fibers to become reentrained during these carpet cleaning activities.

This report presents an evaluation of the concentrations of asbestos fibers in the carpet before and after cleaning by each of the two cleaning methods and a summary of the air monitoring results obtained during cleaning. A complete description of the air monitoring portion of the study is presented in a separate EPA report.<sup>1</sup>

#### OBJECTIVES

A series of controlled experiments in an unoccupied building were performed to evaluate the effectiveness of a HEPA-filtered vacuum cleaner and a HEPA-filtered hot-water extraction cleaner in the removal of asbestos from carpet. A secondary objective was to investigate the potential for the reentrainment of asbestos fibers during carpet-cleaning activities.

## SECTION 2

### CONCLUSIONS AND RECOMMENDATIONS

#### CONCLUSIONS

The following are the principal conclusions reached during this study:

- ° Wet cleaning significantly reduced the asbestos concentration in the carpet by approximately 70 percent. There was no significant change in carpet asbestos concentration after dry-vacuuming.
- ° Both dry vacuuming and wet cleaning of carpet resulted in a statistically significant increase in the airborne asbestos concentration in the area. Airborne asbestos concentrations were two to four times greater during than before the carpet cleaning activities.
- ° Airborne asbestos particles reentrained during carpet-cleaning activities were predominantly smaller than the residual particles in the carpet.
- ° Use of a microvacuuming technique on the carpet tended to recover significantly less asbestos than the bulk-carpet sonic extraction technique.

#### RECOMMENDATIONS

The study conclusions led to the following recommendations:

- ° Further research should be conducted to examine the performance of different HEPA-filtered dry and wet carpet cleaners, e.g., performance as a function of horsepower, static water lift, and operating air volume and velocity. Further study also should be conducted to examine other cleaning methodologies, e.g., repeated carpet cleaning.
- ° Further research is needed to confirm the possible reentrainment of asbestos fibers during actual operating conditions and to determine exposure to custodial workers performing these activities in buildings containing friable asbestos-containing materials.

## SECTION 3

### STUDY DESIGN

#### TEST FACILITY

This study was conducted in an unoccupied building at Wright-Patterson Air Force Base in Dayton, Ohio. Two rooms, each containing approximately 500 square feet of floor space, were constructed in a large bay of the building.

Figure 1 presents the layout of the test facility. The rooms were constructed of 2-in. x 4-in. lumber with studs spaced on 24-in. centers and 3/4-in. plywood floors. The ceiling, floor, and walls were double-covered with 6-mil polyethylene sheeting. (The interior layer of polyethylene sheeting was encapsulated and replaced after each experiment.) Where the joining of separate sheets of polyethylene was necessary, the sheets were overlapped at least 12 in. and joined with an unbroken line of adhesive to prohibit air movement. Three-inch-wide tape was then used for further sealing of the joint on both the inside and outside of the plastic sheeting.

Entry from one room to another was through a triple-curtained doorway consisting of two overlapping sheets of 6-mil polyethylene placed over a framed doorway. Each sheet was secured along the top of the doorway, and the vertical edge of one sheet was secured along one side of the doorway and the vertical edge of the other sheet was secured along the opposite side of the doorway.

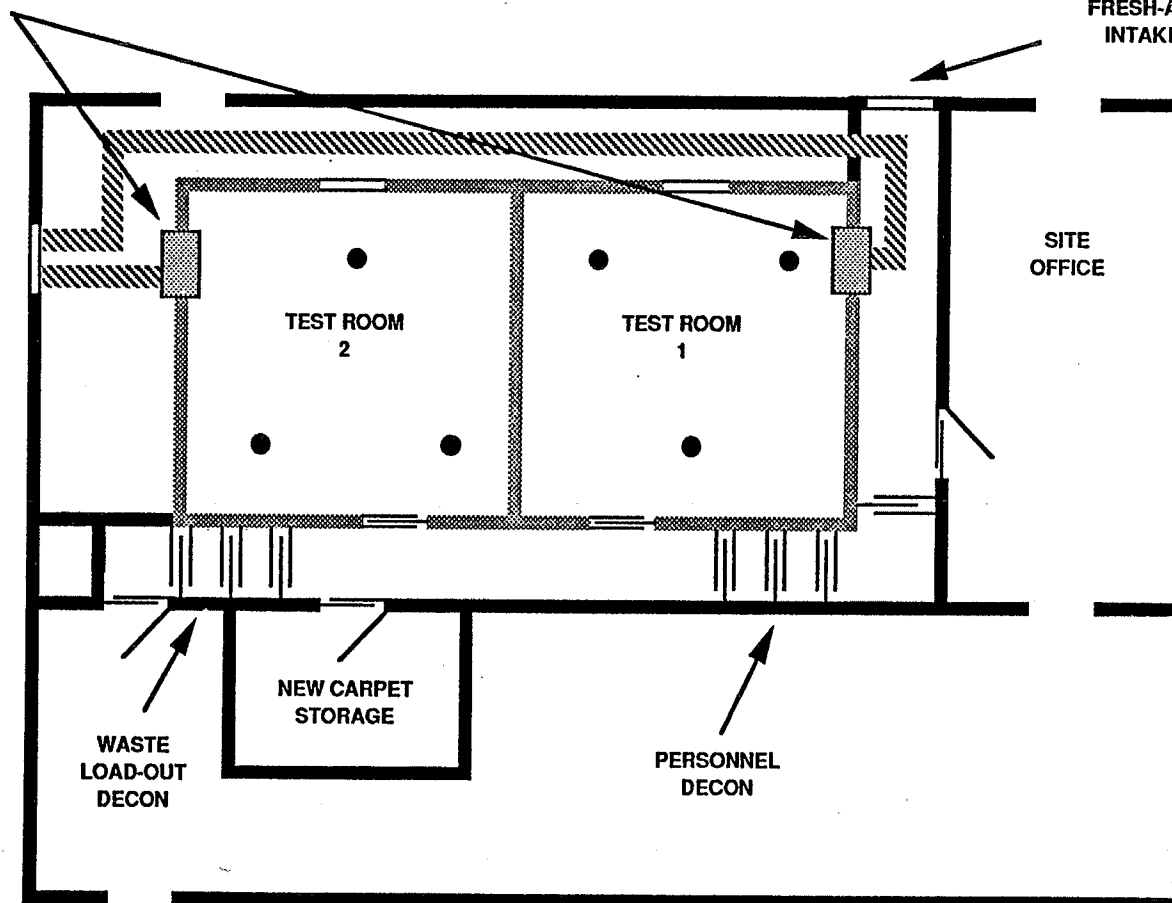
Determination of room size (approximately 29 ft x 17 ft x 7.5 ft) was based on the minimum amount of time required to vacuum or wet-clean the room and to attain an adequate volume of sample air to achieve a specified analytical sensitivity. A 52-inch, ceiling-mounted, axial-flow, propeller fan was installed in each room to facilitate air movement and to minimize temperature stratification.

Separate decontamination facilities for workers and waste materials were connected to the experimental areas. The worker decontamination facility consisted of the following three totally enclosed chambers:

- 1) An equipment-change room with triple-curtained doorways--one to the work area and one to the shower room.
- 2) A shower room with triple-curtained doorways--one to the equipment change room and one to the clean change room. The one shower installed in this room was constructed so that all water was collected and pumped through a three-stage filtration system. The

HEPA-FILTERED  
NEGATIVE AIR  
UNIT

FRESH-AIR  
INTAKE



● = AIR SAMPLE LOCATION

Figure 1. Layout of test facility, Experiments 1 through 16.

three-stage filtration system consisted of a 400-micrometer, nylon-mesh, filter-bag prefilter; a 50-micrometer, filter-bag second-stage filter; and a 5-micrometer final-stage filter. Filtrate was disposed of as asbestos-contaminated waste. Water was drained from the filtration system exit into a sanitary sewerage system.

- 3) A clean change room with triple-curtained doorways--one to the shower room and one to the noncontaminated areas of the building.

### Air Filtration

High-efficiency particulate air (HEPA) filtration systems were used to reduce the airborne asbestos concentrations to background levels after each experiment. These units were operated during both preparation and decontamination of the test rooms. The air filtration units did not operate during the carpet-cleaning phase of each experiment.

One HEPA filtration system was dedicated to each test room (Figure 1). Each unit provided approximately eight air changes every 15-minute period. The negative pressure inside the test rooms ranged from -0.08 to -0.06 in. of water. All exhaust air passed through a HEPA filter and was discharged to the outdoors (i.e., outside the building). All makeup air was obtained from outside the building through a window located on the side of the building opposite the exhaust for the HEPA filtration systems.

## EXPERIMENTAL DESIGN

### Experiments 1 Through 16

Two carpet-cleaning methods--dry vacuuming with a HEPA-filtered vacuum and wet cleaning with a HEPA-filtered hot-water extraction cleaner--were evaluated on carpet artificially contaminated at levels of approximately 100 million and 1 billion asbestos structures per square foot (s/ft<sup>2</sup>). Each combination of cleaning method and contamination level was replicated four times. Four different (same model) HEPA-filtered vacuums and four different (same model) HEPA-filtered hot-water extraction units were used in this study so the results would not be influenced by the peculiarities of a single unit. Each machine was used only once per combination of cleaning method and contamination level. This experimental design, which yielded a total of 16 experiments, is summarized in Table 1.

TABLE 1. EXPERIMENTAL DESIGN FOR EXPERIMENTS 1 THROUGH 16

Approximate contamination level, s/ft <sup>2</sup>	Cleaning method and experiment	
	Wet cleaning	Dry vacuuming
100 million	1, 4, 5, 8	2, 3, 6, 7
1 billion	9, 12, 13, 16	10, 11, 14, 15

Two experiments were conducted during each day of the study. Each combination of cleaning method and contamination level was tested twice in each test room. A single experiment consisted of contaminating a new piece of carpet (approximately 500 square feet) with asbestos fibers, collecting work-area air samples, collecting microvacuum and bulk carpet samples, dry-vacuuming or wet-cleaning the carpet while concurrently collecting a second set of work-area air samples, collecting a second set of microvacuum and bulk carpet samples, removing the carpet, and decontaminating the test room. Each test room was decontaminated by encapsulating the carpet and the polyethylene sheeting on the ceiling and walls prior to their removal. These materials were removed and replaced after each experiment.

#### Experiments 17 Through 24

Eight additional experiments were conducted to evaluate the differences in asbestos retention characteristics of new carpet versus carpet that has been wet-cleaned. These experiments were designed for comparison with Experiments 1 through 16.

Experimental procedures for Experiments 17 through 24 were identical to those in the first 16, except for one difference; prior to contamination, the carpet was dry-vacuumed, wet-cleaned, and then dry-vacuumed again when dry. These experiments were conducted to examine differences in the asbestos fiber retention characteristics of new carpet versus new carpet which had been wet cleaned. These experiments were conducted in the same test area used for Experiments 1 through 16; however, the two 500-ft<sup>2</sup> test rooms were converted to four 160-ft<sup>2</sup> test rooms, each with dimensions of approximately 8 ft x 20 ft. Figure 2 shows the modifications to the two test rooms.

Each of the two cleaning methods was tested at two carpet contamination levels (100 million and 1 billion s/ft<sup>2</sup>). Each cleaning method was tested twice in two different rooms. The same four HEPA-filtered dry vacuums and hot-water extraction cleaners were used. Each machine was used only once for each combination of cleaning method and contamination level. This experimental design, which yielded a total of eight experiments, is summarized in Table 2.

TABLE 2. EXPERIMENTAL DESIGN FOR EXPERIMENTS 17 THROUGH 24

Approximate contamination level, s/ft <sup>2</sup>	Cleaning method and experiment	
	Wet cleaning	Dry vacuuming
100 million	17, 19	18, 20
1 billion	21, 23	22, 24

A single experiment consisted of dry-vacuuming, wet-cleaning, and dry-vacuuming again a new piece of carpet in a previously cleaned room; contaminating the carpet with asbestos fibers; collecting microvacuum and bulk carpet samples; dry-vacuuming or wet-cleaning the carpet; collecting a second set of microvacuum and bulk carpet samples; removing the carpet; and decontaminating the test room. Each test room was decontaminated by encapsulating

HEPA-FILTERED  
NEGATIVE AIR  
UNIT

FRESH-AIR  
INTAKE

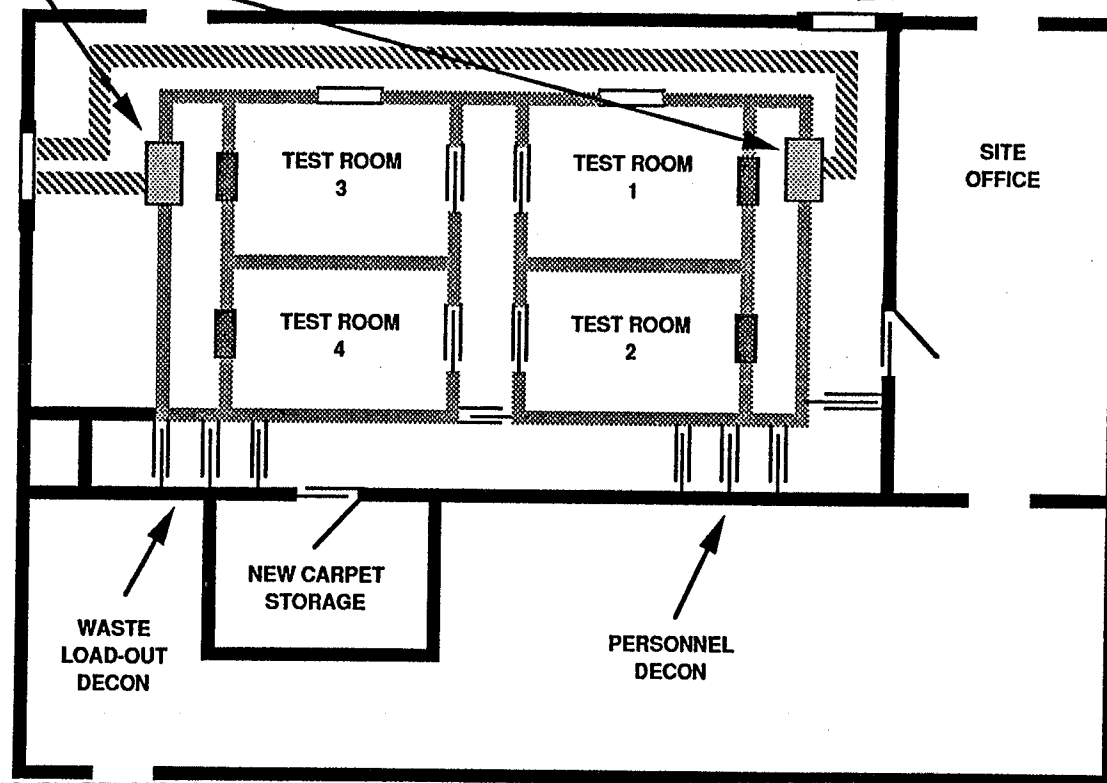


Figure 2. Layout of test facility, Experiments 17 through 24.

the carpet and the polyethylene sheeting on the ceiling and walls prior to their removal. These materials were removed and replaced after each experiment.

## SAMPLING STRATEGY

### Experiments 1 Through 16

#### Carpet Samples --

Bulk carpet and microvacuum samples were collected to establish the pre- and post-cleaning carpet contamination levels. Six samples were collected before and six after cleaning during each experiment.

Power calculations, based on computer simulations, were made to determine the number of samples to be collected before and after cleaning during each experiment. For the purpose of these calculations, the number of experimental replicates was fixed at four. Because little information was available on which to base a sample size determination for carpet sampling, statistical assumptions were based on information from the analysis of air samples.

Inasmuch as measured concentrations were expected to be relatively large (i.e., based on fiber counts of 10 or more), individual measurements from a given carpet were assumed to be lognormally distributed with a coefficient of variation between 0.75 and 1.25. The power calculations were based on transforming each measurement with the log scale and taking an average to give a single measurement for each carpet. A two-sample t-test was then used to compare various sets of four measurements (e.g., before and after cleaning).

Table 3 shows the probability of rejecting, at the 5 percent level, the null hypotheses of no difference between experimental treatments for various combinations of sample size, "true" differences between treatments, and coefficients of variation. The probabilities are overestimates because sources of variability other than sampling and analysis of the carpet were not considered. Variability between different carpets, experimental chambers, cleaning equipment, etc., was not included. Increasing the number of carpet samples, however, would not reduce variability introduced by these other sources. Assuming the other sources of variability are small relative to sampling and analysis variability, Table 3 still provided a useful guide for determining sample size.

Assuming a coefficient of variation of 1.0, six samples taken before cleaning and six samples taken after cleaning gives a probability of approximately 0.84 of obtaining a statistically significant difference when one concentration is half the other (0.5 in Table 3). Detection of more subtle differences in concentration would be unlikely even if the sample size were increased to eight. The chance of detecting a proportional difference of 0.5 decreases rapidly with sample sizes less than six; however, proportional differences of less than 0.33 are detected with high probability with as few as three samples. The number of carpet samples collected is shown in Table 4.

TABLE 3. PROBABILITY OF REJECTING, AT THE 5% LEVEL, THE NULL HYPOTHESIS OF NO DIFFERENCE BETWEEN TWO EXPERIMENTAL TREATMENTS AS A FUNCTION OF THE NUMBER OF CARPET SAMPLES AND THE ACTUAL DIFFERENCE IN ASBESTOS CONCENTRATIONS (CV = 0.75, 1.0, 1.25)

Asbestos level after cleaning as a proportion of asbestos level before cleaning <sup>a</sup>	Number of carpet samples			
	3	5	6	8
CV = 0.75				
0.75	0.27	0.34	0.36	0.52
0.5	0.75	0.88	0.95	0.98
0.33	0.98	1.00	1.00	1.00
0.25	1.00	1.00	1.00	1.00
0.1	1.00	1.00	1.00	1.00
CV = 1.0				
0.75	0.22	0.26	0.28	0.32
0.5	0.60	0.75	0.84	0.90
0.33	0.87	0.98	0.99	1.00
0.25	0.98	1.00	1.00	1.00
0.1	1.00	1.00	1.00	1.00
CV = 1.25				
0.75	0.16	0.19	0.21	0.26
0.5	0.49	0.64	0.71	0.82
0.33	0.77	0.94	0.97	0.99
0.25	0.91	0.99	1.00	1.00
0.1	1.00	1.00	1.00	1.00

<sup>a</sup> For example, 0.25 means that an initial concentration of 100 million fibers per square foot before cleaning is reduced to 25 million fibers per square foot after cleaning.

TABLE 4. NUMBER OF CARPET SAMPLES COLLECTED IN EXPERIMENTS 1 THROUGH 16

Type	Number of samples		
	Before cleaning	After cleaning	Field blanks
Microvacuum	192	192	24
Bulk carpet	192	192	-
Total samples	384	384	24

The carpet was divided into 400 1-ft<sup>2</sup> areas (a 16-ft by 25-ft grid) by using a string grid system. The carpet was then stratified into three pairs of equally sized sections. One bulk carpet sampling location and one microvacuum sampling location were selected at random within each of the six sections. This sampling strategy assured representative samples from the entire piece of carpet.

#### Air Samples --

Work-area air samples were collected to establish airborne asbestos concentrations before and during cleaning. For each experiment, three air samples were collected before and three during cleaning. A total of 96 air samples were collected.

#### Experiments 17 Through 24

Bulk carpet and microvacuum samples were again collected to establish the pre- and post-cleaning carpet contamination levels. During each experiment, four samples were collected before and four after carpet cleaning. The number of carpet samples collected in Experiments 17 through 24 is shown in Table 5.

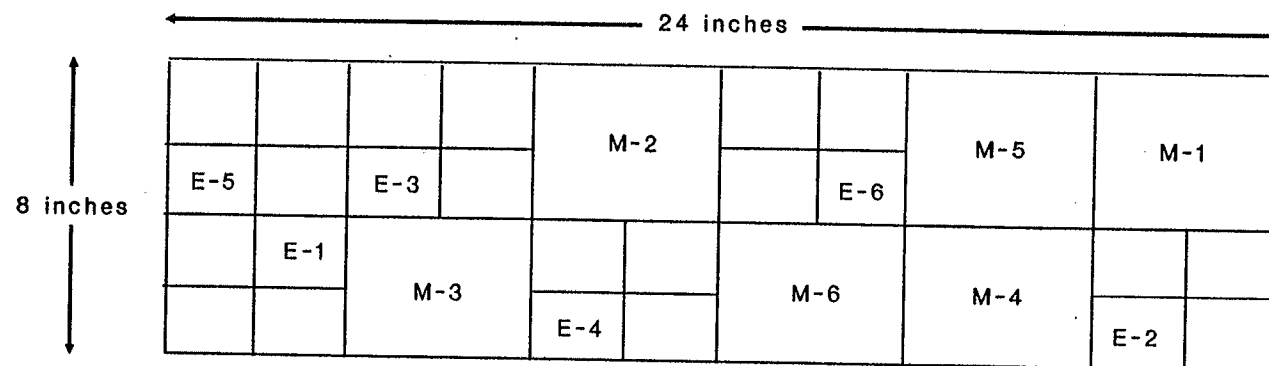
TABLE 5. NUMBER OF CARPET SAMPLES COLLECTED IN  
EXPERIMENTS 17 THROUGH 24

Type	Number of samples		
	Before cleaning	After cleaning	Field blanks
Microvacuum	32	32	4
Bulk carpet	32	32	4
Total samples	64	64	8

The carpet was divided into 160 1-ft<sup>2</sup> areas (an 8-ft by 20-ft grid) by using a string grid system. The carpet was then stratified into fourths. One bulk carpet sampling location and one microvacuum sampling location were selected at random within each of the four sections. This sampling strategy assured representative samples from the entire piece of carpet.

#### PRELIMINARY SAMPLING AND ANALYTICAL PERFORMANCE STUDY

Preliminary experiments were conducted to document the performance of the microvacuum sampling and sonic extraction techniques for the recovery of asbestos from carpet. The precision and level of recovery of asbestos by these two methods were determined by contaminating an 8-inch by 24-inch strip of carpet with approximately 1 billion s/ft<sup>2</sup> and then collecting samples for analysis by both techniques. Six microvacuum samples were collected from 10-cm by 10-cm sections of the contaminated carpet. Bulk samples for analysis by sonic extraction were collected from 2-inch by 2-inch sections of the contaminated carpet. Sample locations, which were randomly chosen from the contaminated carpet, are shown in Figure 3.



M - Micro-Vac Sample  
E - Sonic Extraction Sample

Figure 3. Sample locations for preliminary performance experiments on the microvacuum and sonic extraction sampling and analytical techniques.

Each carpet sample was analyzed in triplicate to assess the precision of each method. Individual sample results are presented in Appendix A.

The data were analyzed by standard analysis of variance (ANOVA) techniques. Data from each method were analyzed separately by a one-way ANOVA with a random effects model. These results are summarized in Table 6. For each method, the between-sample variation contributed to most of the variation, which suggests that the variation between different locations in the carpet was greater than the variation between different preparations of the same sample. These results indicate that increasing the number of carpet samples would have a greater impact on the precision of both methods than would increasing the number of replicate analyses of the same sample. The calculated coefficient of variation (CV) for the microvacuum technique (166 percent) was four times larger than the CV for the sonic extraction procedure (43 percent). Figure 4 shows the mean recoveries from each method. Microvacuuming the carpet recovered significantly less asbestos than the bulk-carpet sonic extraction procedure. The mean asbestos recovery obtained with the microvacuum technique was 23 million s/ft<sup>2</sup>, whereas approximately 794 million s/ft<sup>2</sup> was obtained with the sonic extraction technique. Based on the superior precision and performance of the sonic extraction technique for asbestos recovery from carpet, only the sonic extraction method was used to analyze the carpet samples; all microvacuum samples collected during this research study were archived for future consideration.

#### SAMPLE SIZE REVISIONS

The preliminary experiments conducted to assess the performance of the sonic extraction technique for asbestos recovery from carpet provided useful information on the variability associated with this analytical technique that was not available when the sampling strategy was being developed. The calculated coefficient of variation associated with this method was 43 percent. The original sample size calculations for this study assumed a CV of 100 percent. Table 7 shows the results of new calculations for a different range of CVs based on the results of the performance study. Assuming a CV of 40 percent, three samples collected before cleaning and three samples collected after cleaning give a probability of approximately 0.99 of obtaining a statistically significant difference when one concentration is half the other. Therefore, rather than analyze all six sets of samples collected before and after cleaning, three sets of samples were randomly selected from each of the 24 experiments to be analyzed. This provided a total of 144 estimates of carpet contamination (72 estimates before cleaning and 72 estimates after cleaning).

The use of these preliminary results to modify the number of samples needed to achieve statistical significance greatly reduced analytical costs and turnaround time during this study.

TABLE 6. VARIANCE COMPONENTS ANALYSIS COMPARING PERFORMANCE OF MICROVACUUM AND SONIC EXTRACTION FOR ASBESTOS RECOVERY FROM CARPET

Method	Variance components			Overall mean, million s/ft <sup>2</sup>	CV, %
	Between samples	Within sample	Total		
Sonic Extraction	103,913	10,900	114,813	794	43
Microvacuum	1,145	305	1,449	23	166

TABLE 7. PROBABILITY OF REJECTING, AT THE 5% LEVEL, THE NULL HYPOTHESIS OF NO DIFFERENCE BETWEEN TWO EXPERIMENTAL TREATMENTS AS A FUNCTION OF THE NUMBER OF CARPET SAMPLES AND THE ACTUAL DIFFERENCE IN ASBESTOS CONCENTRATIONS (CV = 0.3, 0.4, 0.75)

Asbestos level after cleaning as a proportion of asbestos level before cleaning <sup>a</sup>	Number of carpet samples		
	2	3	6
CV = 0.3			
0.75	0.54	0.68	0.90
0.5	0.98	1.00	1.00
0.33	1.00	1.00	1.00
0.25	1.00	1.00	1.00
0.1	1.00	1.00	1.00
CV = 0.4			
0.75	0.36	0.49	0.73
0.5	0.93	0.99	1.00
0.33	1.00	1.00	1.00
0.25	1.00	1.00	1.00
0.1	1.00	1.00	1.00
CV = 0.75			
0.75	0.18	0.23	0.36
0.5	0.58	0.75	0.93
0.33	0.91	0.98	1.00
0.25	0.96	1.00	1.00
0.1	1.00	1.00	1.00

<sup>a</sup> For example, 0.25 means that an initial concentration of 100 million fibers per square foot before cleaning is reduced to 25 million fibers per square foot after cleaning.

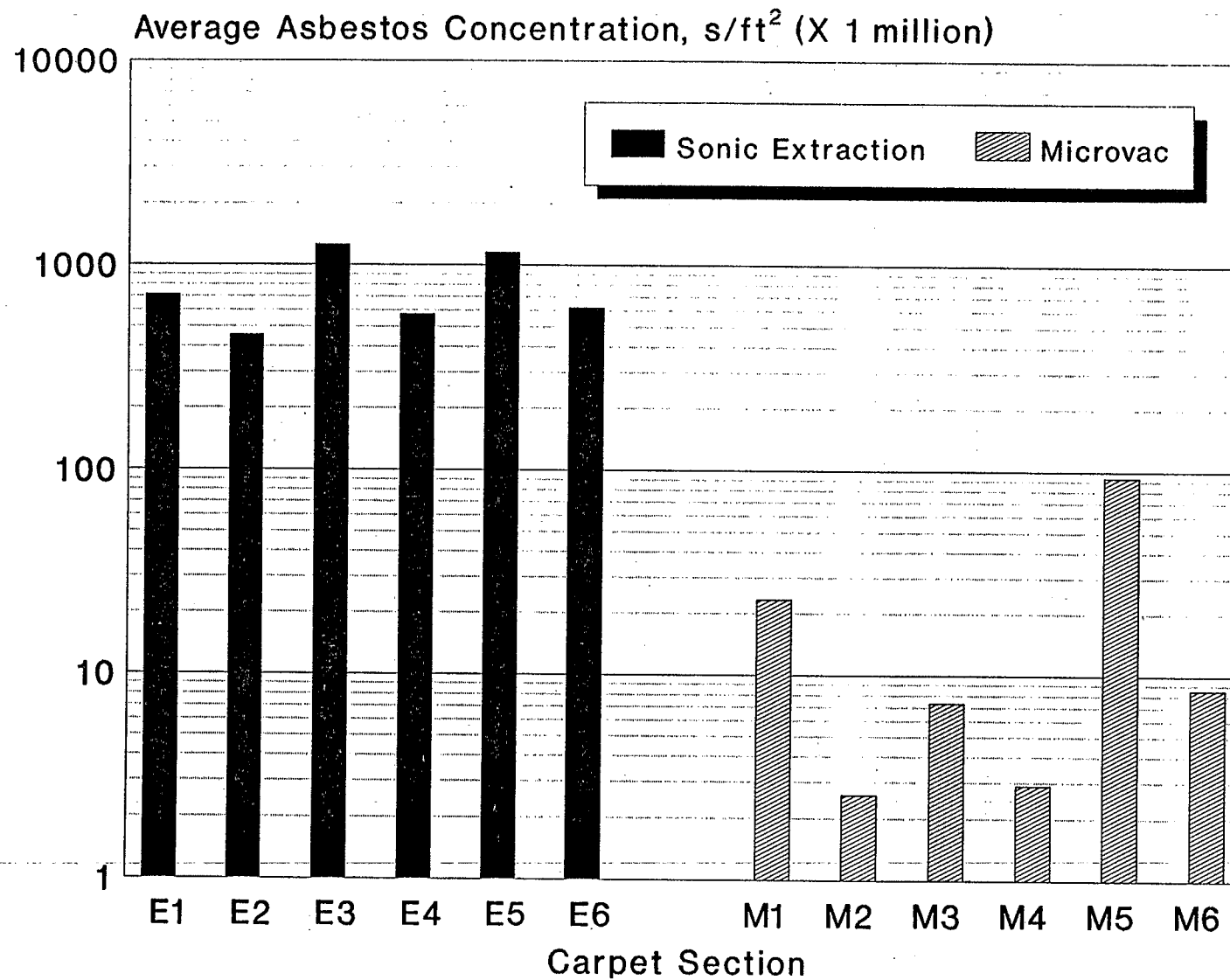


Figure 4. Average asbestos concentration in carpet samples from preliminary performance experiments with the microvac and sonic extraction sampling and analytical techniques.

## SECTION 4

### MATERIALS AND METHODS

A survey was made of 14 General Service Administration (GSA) field offices in 11 States distributed across the United States to determine the type of carpet, HEPA-filtered vacuum, and HEPA-filtered hot-water extraction unit to use in this study. Building managers were asked to identify 1) the specific type and manufacturer of carpet used in GSA buildings, 2) the manufacturer and model of HEPA-filtered vacuum cleaner commonly used, and 3) the manufacturer and model of HEPA-filtered hot-water extraction unit routinely used in their buildings.

None of the GSA offices routinely wet-cleaned their carpet. When wet-cleaning was necessary, contractors were hired to perform the work. Therefore, six trade associations (the American Institute of Maintenance, the Building Service Contractors Association, the International Maintenance Institute, the Environmental Management Association, the International Sanitary Supply Association, and the Vacuum Cleaner Manufacturers Association) were surveyed to obtain their recommendations on a HEPA-filtered hot-water extraction cleaner.

#### SELECTION OF CARPET

Eight GSA offices indicated a preference for the same manufacturer and type of carpet. The selected carpet was first-grade, 100 percent nylon, with 0.25-inch cut pile, 28 ounces of yarn per square foot, and dual vinyl backing. The carpet was manufactured in roll sizes of 4.5 by 90 ft.

#### SELECTION OF CARPET CLEANING EQUIPMENT

##### HEPA-Filtered Vacuum

The HEPA-filtered vacuum selected for this study was the model most frequently mentioned in the GSA survey. The unit had an airflow capacity of 87 cubic feet per minute, a suction power of 200 watts, and 75 inches static water lift. (Water lift is the maximum amount of force a vacuum can exert throughout the system if the end of the vacuum hose is completely closed off.) This unit was also equipped with a motor-driven carpet nozzle with a rotating brush.

## Hot-Water Extraction Cleaner

Three of the trade associations surveyed recommended the same hot-water extraction unit. The selected cleaner was equipped with a HEPA-filtered power head with a moisture-proof, continuous-duty, 2-horsepower vacuum motor that develops a 100-inch static waterlift. This unit was also equipped with an extractor tool that uses a motor-driven cylindrical nylon-bristle brush, 4 inches in diameter by 14 inches long, to agitate and scrub the carpet during the extraction process.

## SAMPLING METHODOLOGY

### Bulk Carpet Samples

Carpet samples were collected before and after cleaning by using a 100-cm<sup>2</sup> (4-in.<sup>2</sup>) template and a utility razor knife. Each carpet sample was cut in half, providing a duplicate sample for archiving. Each piece of carpet was placed in a separate labeled container. Wide-mouth polyethylene jars with polypropylene screw caps were used to contain the carpet samples. The template and utility razor were thoroughly cleaned prior to sample collection to reduce the possibility of cross-sample contamination.

### Microvacuum Samples

Microvacuum samples were collected by vacuuming a 100-cm<sup>2</sup> area of carpet with a membrane filter air-sampling cassette and a vacuum pump. The sampling assembly consisted of a 25-mm-diameter, 0.45- $\mu$ m pore-size, mixed cellulose ester membrane filter with a 5- $\mu$ m pore-size mixed cellulose ester backup diffusing filter and cellulose ester support pad contained in a three-piece cassette. The cassette was connected to an electric-powered sampling pump with flexible tubing. The pump and cassette assembly was calibrated to 10 liters per minute. The 100-cm<sup>2</sup> area was vacuumed by dragging the filter cassette across the carpet to agitate the carpet pile. The carpet was vacuumed for 30 seconds in one direction, and another 30 seconds in a direction 90 degrees to the first. After 1 minute of vacuuming, the pump was turned off and the filter cassette was labeled and sealed.

### Air Samples

Air samples were collected on open-face, 25-mm-diameter, 0.45- $\mu$ m-pore-size, mixed cellulose ester membrane filters with a 5- $\mu$ m pore-size, mixed cellulose ester backup diffusing filter, and cellulose ester support pad contained in a three-piece cassette. The filter cassettes were positioned approximately 5 feet above the floor with the filter face at approximately a 45-degree angle toward the floor. The filter assembly was attached to an electric-powered vacuum pump operating at a flow rate of approximately 10 liters per minute. In each test room, the air samplers were positioned in a triangular pattern (Figure 1). Air samples were collected for a minimum of 65 minutes before and during carpet cleaning to achieve a minimum air volume of approximately 650 liters. The sampling pumps were calibrated both before and after sampling with a precision rotameter.

## ANALYTICAL METHODOLOGY

### Bulk Carpet Samples

A sonication procedure developed by McCrone Environmental Services, Inc., was used to extract asbestos particles from the bulk carpet samples for subsequent analysis by transmission electron microscopy (TEM). The laboratory preparation procedure is as follows:

- 1) The carpet sample was placed carpet-side down in a 1000-ml beaker containing 100 ml of a 0.1 percent solution (by volume) of Aerosol OT (a commercial surfactant) made with deionized particle-free water.
- 2) The beaker containing the carpet sample and Aerosol OT solution was ultrasonicated three times, 10 minutes each time. After each sonication, the solution was drained into the 500-ml polyethylene screw cap sample container and another 100 ml of fresh Aerosol OT solution was added for the next sonication.
- 3) The carpet sample was then removed from the beaker. The beaker was rinsed with 100 ml of deionized particle-free water. The rinse from the beaker was added to the sample container. The carpet sample was dried and stored.
- 4) The resulting suspension was shaken vigorously to disperse the fibers evenly and then allowed to sit for 2 minutes while the large or heavy particles settled or rose. A measured volume of this suspension was extracted with a disposable graduated pipette from  $\frac{1}{4}$  to  $\frac{1}{2}$  inch below the water surface. The aliquot was then filtered onto a 0.22- $\mu$ m-pore-size mixed cellulose ester filter backed by a 0.45- $\mu$ m-pore-size mixed cellulose ester filter. Three measured aliquots of different volumes were generally sufficient to attain a good fiber loading on a filter.
- 5) An optional step for removal of very large nonasbestos structures from the sample solution before filtration was occasionally included in the preparation procedure. This involved passing the solution through a coarse-mesh stainless steel or plastic screen prior to filtration. The screen was thoroughly cleaned or replaced before each sample.
- 6) When filtration was complete, the 0.22- $\mu$ m filter was carefully removed from the funnel assembly and placed in a Gelman "Analyslide" dish. The filter was dried in a closed container with a dessicant. (Some of the filters were dried by placing the dish holding the filter on a hot plate at low temperature.)
- 7) Portions of the filter were prepared for TEM analysis in accordance with the NIOSH 7402 preparation procedure. At least two 200-mesh TEM grids from different areas of the filter were prepared for each sample.

Asbestos structures were counted and identified in accordance with the EPA provisional method, Level II.<sup>2</sup> Only asbestos structures were counted because the carpet samples often contained a significant number of clay fibers and other nonasbestos structures. McCrone Environmental Services, Inc., performed the TEM analyses on the carpet samples under separate contract with EPA's Risk Reduction Engineering Laboratory in Cincinnati.

#### Microvacuum Samples

The mixed cellulose ester filters used to collect the microvacuum carpet samples were analyzed by TEM. These samples were prepared according to the analytical laboratory's Standard Operating Procedure for dust sample collection. Counting and identification of the asbestos structures were performed in accordance with EPA provisional method, Level II. McCrone Environmental Services, Inc., performed the TEM analyses on the microvacuum samples under separate contract with EPA's Risk Reduction Engineering Laboratory in Cincinnati.

#### Air Samples

The mixed cellulose ester filters were analyzed by transmission electron microscopy (TEM). These filters were prepared and analyzed in accordance with the nonmandatory TEM method as described in the Asbestos Hazard Emergency Response Act (AHERA) final rule (52 CFR 41821). Battelle Laboratories, Columbus Division, performed the TEM analyses on the field samples under separate contract with EPA's Risk Reduction Engineering Laboratory (RREL) in Cincinnati.

### STATISTICAL ANALYSIS

#### Carpet Samples

A single estimated concentration was obtained before and after cleaning during each experiment by taking the arithmetic mean of the individual estimates. This gave 24 pairs of concentrations, one for each experiment. The natural logarithm of each of the 48 concentrations was used for subsequent statistical analyses. This is equivalent to assuming that the data follow a lognormal distribution. The lognormal distribution is commonly assumed for measurements of asbestos and other air pollutants.

The geometric mean and a 95 percent confidence interval were calculated for each contamination level and cleaning method. A three-way analysis of variance (ANOVA)<sup>3</sup> with contamination level (low, high), cleaning method (wet, dry), and experimental set (1 to 16, 17 to 24) as the three experimental factors was performed on the difference (on the log scale) between the concentration before cleaning and the concentration after cleaning. (The difference on the log scale is equivalent to the ratio on the original scale.) A 95 percent confidence interval for the difference in concentration before and after cleaning was calculated by using the error mean square of the

analysis of variance. Results were transformed back to the original scale for reporting purposes.

#### Air Samples

Airborne asbestos concentrations were determined before and during carpet cleaning to study the effect of the cleaning method and contamination loading on fiber reentrainment during carpet cleaning. Three work-area samples were collected before and during carpet cleaning for each experiment. A single estimate of the airborne asbestos concentrations before and during cleaning was then determined by averaging the three respective work-area samples. The natural logarithm of each of the concentrations was used for subsequent statistical analyses. This is equivalent to assuming that the data follow a lognormal distribution. A two-factor ANOVA with cleaning method (wet, dry) and contamination level (low, high) as the experimental factors was performed on the difference (on the log scale) between the concentration before cleaning and the concentration during cleaning.

SECTION 5  
EXPERIMENTAL PROCEDURES

PRESTUDY AIR MONITORING

Before construction of the contamination enclosure system, air samples were collected to determine a baseline airborne asbestos concentration inside the test facility. Seven interior air samples and two field blanks were collected in accordance with sampling procedures described in Section 4. The air samples were collected for a period of approximately 200 minutes to achieve a minimum air volume of 1260 liters for each sample. These samples were analyzed in accordance with the nonmandatory TEM method, as described in the AHERA final rule.

The average airborne asbestos concentration for the seven samples collected was 0.0031 s/cm<sup>3</sup>. The TEM analysis of the seven samples yielded a total of 6 asbestos structures (4 chrysotile and 2 amphibole). One chrysotile fiber was detected on each field blank. Table 8 summarizes these results.

TABLE 8. SUMMARY OF PRESTUDY AIRBORNE ASBESTOS  
CONCENTRATIONS IN TEST FACILITY

Sample	Number of structures observed	Concentration, s/cm <sup>3</sup>
001	1	0.0028
002	0	<0.0039
003	2	0.0077
004	0	<0.0038
005	1	0.0039
006	1	0.0039
007	1	0.0038
Field blank	1	-
Field blank	1	-

## CARPET CONTAMINATION

Selected levels of carpet contamination for this study were based on field data reported by Wilmoth et al.<sup>4</sup> Asbestos concentrations ranging from approximately 8000 s/ft<sup>2</sup> to 2 billion s/ft<sup>2</sup> were detected in the contaminated carpet by use of a microvac technique. Bulk sample sonication of the samples revealed levels ranging from 30 million to 4 billion s/ft<sup>2</sup>. Based on these preliminary results, the target experimental asbestos contamination levels of approximately 100 million and 1 billion s/ft<sup>2</sup> were believed to represent carpet contamination likely to be present in buildings where asbestos-containing materials are present.

The carpet was contaminated with a spray-applied dispersion of Union International Centre le Centre Calidria chrysotile asbestos in distilled water. The asbestos was dispersed uniformly on the carpet by use of a manual pesticide sprayer equipped with a stainless steel container.

### Preparation of Concentrated Aqueous Suspensions of Chrysotile

Aqueous suspensions of chrysotile are not stable for long periods unless they are specially prepared.<sup>5</sup> Even small amounts of high-molecular-weight organic materials, such as those generated by bacteria, result in the destabilization of chrysotile suspensions and the attachment of fibers to the walls of the container. This process can be reversed only by carrying out oxidation of the organic materials with ozone and ultraviolet light treatment.<sup>5</sup> If precautions are taken to exclude all organic materials and to prevent bacterial growth, however, chrysotile suspensions can be prepared that remain stable for several years. This can be achieved by sterilizing all containers used in the preparation, using freshly distilled water for the dispersion process, and storing the preparation in flame-sealed glass ampules that are autoclaved immediately after sealing.

For this project, the decision was made to prepare sealed ampules of fiber dispersions so that the contents of one ampule dispersed in 6 liters of freshly distilled water would provide the concentration of suspension required for artificial contamination of one 500-ft<sup>2</sup> sample of carpet. Calculations of the amount of chrysotile required were based on the assumption that all of the fibers needed to contaminate one carpet sample would be contained in a volume of 50 ml sealed in one ampule.

For the higher of the two concentrations used, the fiber concentration required in each ampule was calculated as follows:

Higher contamination level required	= $10^9$ fibers/ft <sup>2</sup>
Number of fibers required to contaminate 500 ft <sup>2</sup>	= $6.5 \times 10^{11}$ fibers
Fiber concentration required for this number of fibers to be in a volume of 50 ml	= $1.3 \times 10^{13}$ fibers/liter

The lower of the two concentrations used was a factor of 10 lower than this. As a way of ensuring an exact factor of 10 ratio between the two concentrations, the lower-concentration dispersion was prepared by diluting an aliquot of the high-concentration dispersion.

Because the original suspension was to be prepared by dispersing a known weight of chrysotile in water, knowledge of what numerical concentration of fibers would result from this dispersion was required. Previous work on preparation of ampules indicated that a suspension of purified Calidria chrysotile in water with a mass concentration of 1 µg/liter yielded a numerical fiber concentration of approximately 200 million fibers per liter. Based on this conversion, the weight of chrysotile is calculated as follows:

$$\begin{aligned}\text{Weight required} &= 1.3 \times 10^{13} \times 10^{-6} / (2 \times 10^8) \text{ g/liter} \\ &= 65 \text{ mg/liter}\end{aligned}$$

Therefore, the preparation of 1.5 liters of a suspension with this concentration requires 97.5 mg of chrysotile.

The calculation for determining the mass of chrysotile required is based on data from very dilute suspensions. Initial experiments indicated that some difficulty could arise in obtaining complete dispersal of the chrysotile at the high concentrations in this program; if some aggregation were to occur, the numerical structure count would be somewhat lower than that required. For this reason, the suspensions were prepared to have a higher mass concentration than that indicated in the preceding calculation.

Before the fiber suspensions were prepared, the 50-ml ampules were thoroughly cleaned. Each ampule was filled to the top with freshly distilled water and placed in an ultrasonic bath for a period of 15 minutes; the water was then removed by suction. This process was repeated twice before the ampules were considered ready for filling.

The higher-concentration chrysotile suspension was prepared first. All water used for preparation of these dispersions was freshly distilled (within 8 hours of preparation). A weight of 409.5 mg of purified Calidria chrysotile was placed in an agate mortar and lightly ground with a small volume of water by use of a pestle. More freshly distilled water was added gradually until a creamy liquid was obtained. Up to 400 ml of this liquid was made up in a disposable polypropylene beaker, and the beaker was placed in an ultrasonic bath for approximately 30 minutes. Up to 1500 ml of the chrysotile suspension was then made up with water in a 1-gallon polyethylene bottle. The bottle was placed in an ultrasonic bath for approximately 30 minutes, during which time the bottle was removed several times and shaken vigorously. The lower-concentration suspension (a volume of 150 ml) was made up to 1500 ml with water in another 1-gallon polyethylene bottle. The two suspensions had concentrations of 273 and 27.3 mg/liter, respectively.

A disposable polyethylene funnel was used to place a volume of 50 ml of suspension in each of the ampules. This left adequate space in the ampule to

permit efficient shaking of the contents. The filled ampules were immediately flame-sealed and then autoclaved for 30 minutes at a temperature of 121°C to sterilize the contents. After the ampules cooled, they were labeled in the order of their filling.

#### Preparation of Asbestos Dispersion

The following steps were followed precisely in the preparation of the asbestos dispersions used to contaminate the carpet:

1. All water used for dilution of the ampules of chrysotile suspension was freshly distilled from a glass still.
2. Before the ampule was opened, it was shaken vigorously for 1 minute and then placed in an ultrasonic bath for 30 minutes. During the ultrasonic treatment, the ampule was removed every 5 minutes and again shaken vigorously for 1 minute.
3. A new 32-ounce glass bottle was washed with several changes of freshly distilled water. The ampule was then opened, and the entire contents were emptied into 450 ml of freshly distilled water in the glass bottle. For the high-concentration ampules only, the pH was adjusted to approximately 4.0 by adding 300 to 400  $\mu$ l of glacial acetic acid. The bottle was capped, shaken vigorously, and then placed in an ultrasonic bath for 15 minutes. No surface-active agents were added.
4. The pesticide sprayer was sterilized and cleaned by rinsing it with a 10 to 15 percent solution of Clorox for approximately 15 minutes. The sprayer, including the interior of the outlet pipe, was then thoroughly washed with several changes of freshly distilled water.
5. The sprayer was filled with 5.5 liters of freshly distilled water, and the contents of the bottle were added. The sprayer was then shaken before the carpet was sprayed.

The sprayer was not allowed to dry before it was washed after each experiment because chrysotile is much more difficult to remove from the interior surfaces when it has dried.

To ensure that no bacterial growth had occurred in the sprayer between uses, the inside of the sprayer and the outlet pipe were treated with a 10 to 15 percent solution of Clorox to remove any bacteria and their byproducts. Any bacterial growth would scavenge fibers from the suspension and cause fibers to become attached to the wall of the container. The container and outlet pipe were then rinsed with isopropyl alcohol.

#### Concentrations of Suspensions

Several of the ampules were used to make precise measurements of the fiber concentrations and to determine the fiber size distributions. To

measure these very high fiber concentrations required a total dilution factor of 1 in 25,000 for the low-concentration ampules and 1 in 250,000 for the high-concentration ampules. This was achieved by successive dilutions in freshly distilled water. For the low-concentration ampules, the contents of one ampule were first dispersed in 500 ml. In the second dilution, 10 ml was diluted to 500 ml, and 10 ml of this second dilution was then diluted to 500 ml. Three filters were prepared from this final suspension in accordance with the EPA Analytical Method for Determination of Asbestos Fibers in Water.<sup>6</sup> For the high-concentration ampules, the final suspension was diluted by a further factor of 10 before the filters were prepared.

The dilution factors and the volumes of suspension filtered were selected to yield fiber counts of approximately 40 per grid opening. One fiber count incorporating approximately 600 asbestos structures was made for each of the two concentrations.

The high-concentration ampules yielded asbestos structure counts significantly lower than those obtained during the initial tests on the suspension at the time the ampules were prepared. This effect was investigated and found to have been caused by a rise in pH of the suspension after packing and autoclaving. The increase in the pH was probably due to some leaching of the chrysotile during the autoclave treatment, which caused destabilization of the dispersion and aggregation of the fibers into bundles and clusters. The effect was found to be reversible by adjusting the pH of the dispersion to approximately 4.0 with acetic acid at the time of the first dilution. The measurements on the high-concentration ampules were repeated; another ampule was used and the pH was adjusted during preparation of the first dilution. The aggregation effect did not occur in the low-concentration ampules; therefore, no pH adjustment was required when these ampules were used.

Table 9 shows the results of the fiber concentration measurements made on the low- and high-concentration ampules. The analysis of the laboratory dilution was continued for approximately 600 chrysotile structures to provide a precise concentration value and a size distribution with a sufficient number of structures in each size classification. Appendix B contains the size distributions for the measurements made on the low- and high-concentration ampules. Figure 5 shows the fiber size distribution in the low- and high-concentration ampules.

#### Application of Dispersion to Carpet

A meticulously cleaned hand-pumped garden sprayer was used to apply the asbestos dispersion to the carpet. A fixed number of pumps was used for each batch to provide consistent spray pressure. The desired controlled spray was experimentally determined by trial and error before the tests with asbestos began. The pressure was kept within the desired range by adding a fixed number of pump strokes after each fixed area was sprayed in a predetermined pattern by following a grid work of string placed over the carpet before the

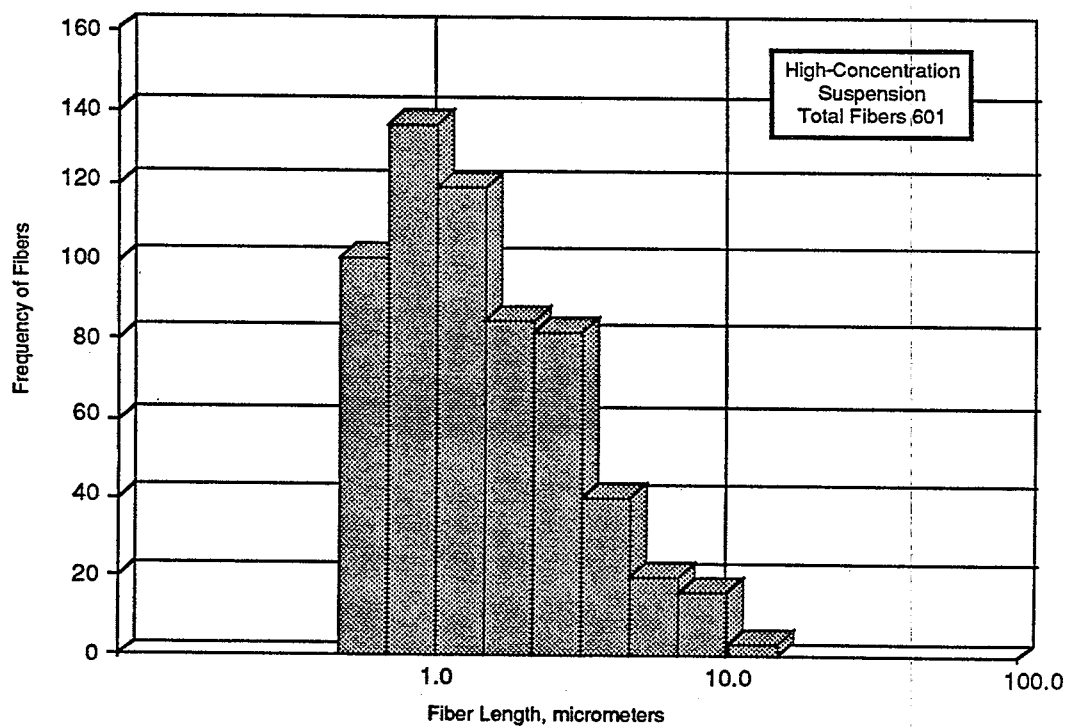
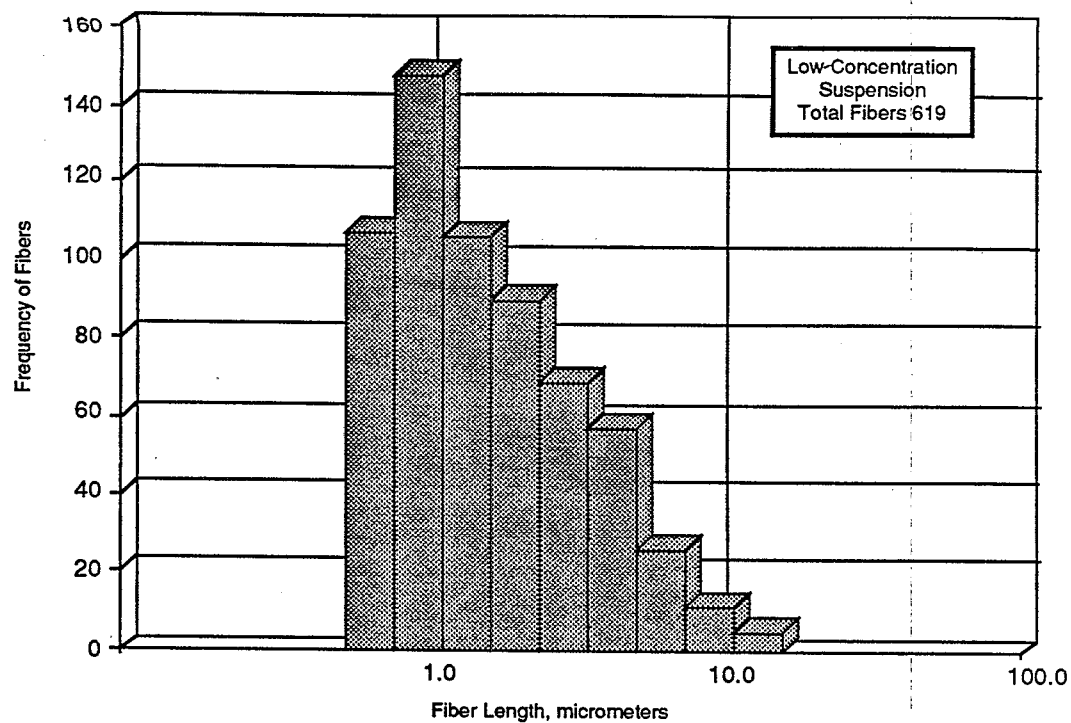


Figure 5. Distribution of chrysotile fiber lengths in the low and high concentration aqueous asbestos suspensions.

beginning of each experiment. The tank was periodically agitated to help keep the asbestos fibers suspended. Dehumidifiers were placed in the room overnight to aid in drying the carpet. The following day a 200-pound steel lawn roller was rolled over the carpet surface to simulate the effects of normal foot traffic in working the asbestos into the carpet.

TABLE 9. SUMMARY OF RESULTS OF TRANSMISSION ELECTRON MICROSCOPY ANALYSES FOR LOW- AND HIGH-CONCENTRATION AMPULES

Sample description	Fiber type	Structure concentration, $10^{12}$ structures/liter					No. of structures counted
		Mean	95% confidence interval	Analytical sensitivity	Equivalent volume sampled, $\mu$ l		
Low-concentration ampule	Chrysotile	2.2	2.0-2.5	0.0036	0.400		619
High-concentration ampule	Chrysotile	25	22-27	0.0409	0.040		601

#### Carpet Cleaning Technique

The carpet was vacuumed or wet-cleaned for a period of approximately 65 minutes to allow the collection of a sufficient volume of air samples to obtain an analytical sensitivity of  $0.005 \text{ s/cm}^3$  of air. The carpet was cleaned in two directions, the second at a 90-degree angle to the first.

#### DISPOSAL OF ASBESTOS-CONTAINING MATERIAL

Asbestos-contaminated materials, including carpeting, polyethylene, protective clothing, etc., were placed in disposable 6-mil polyethylene bags and labeled according to EPA regulations. When filled, the disposal bags were sealed, sponged clean, and moved from the test room to the primary waste-loadout work area (Figure 1). The disposal bags were then sponged a second time, taken through the equipment-change area, and placed in the shower chamber for a thorough washing. The cleaned disposal bags were taken into the clean chamber, loaded into a fiberboard drum, labeled with an EPA-approved asbestos warning label, and transported to a disposal site approved by the Ohio EPA.

#### SITE CLEANUP

Prior to removal of the primary polyethylene barrier (i.e., the first barrier installed to isolate the work area, including test rooms), the surface was thoroughly wet-wiped with amended water. The HEPA filtration system continued to operate during site cleanup.

All debris and waste resulting from the experiments were removed from the building. All the drummed waste was removed from the site and disposed of in a landfill approved by the Ohio EPA.

#### POSTSTUDY AIR MONITORING

After removal of the polyethylene sheeting from the floor, ceiling, and walls, air samples were collected to determine the airborne asbestos concentrations inside the building. Four interior air samples were collected in accordance with the sampling procedures described in Section 5. These samples were collected for a period of approximately 180 minutes to achieve a minimum air volume of approximately 1800 liters for each sample. These samples were analyzed in accordance with the nonmandatory TEM method as described in the AHERA Final Rule. No asbestos was detected in any of these samples.

## SECTION 6

### QUALITY ASSURANCE

The Quality Assurance Project Plan (QAPP) contains complete details of the quality assurance procedures followed during this research project. The procedures used for this study are summarized in the following subsections.

#### SAMPLE CHAIN OF CUSTODY

Sample chain-of-custody procedures were an integral part of both sampling and analytical activities during this study. They were followed for all air and bulk samples collected. The applied field custody procedures documented each sample from the time of its collection until its receipt by the analytical laboratory. Internal laboratory records then documented the custody of the sample through its final disposition.

Standard sample custody (traceability) procedures were used. Each sample was labeled with a unique project identification number, which was recorded in the field log book along with other information specified by the QAPP.

#### QUALITY ASSURANCE SAMPLE ANALYSES

Specific quality assurance procedures for ensuring the accuracy and precision of the TEM analyses of carpet samples included the use of laboratory blanks and duplicate counting.

##### Laboratory Blanks

A sample blank was prepared and analyzed for every 10 carpet samples analyzed. Each blank was prepared in a manner identical to that used for the carpet samples, although no carpet segment was actually used. These blanks served as a quality control check on contamination from the solutions, glassware, filters, and handling procedures. Analysis of 10 TEM grid openings per blank showed all laboratory blanks to be free of asbestos fiber contamination.

##### Duplicate Sample Analyses

Duplicate sample analysis provides a means of quantifying any analytical variability introduced by the preparation procedure and refers to the analysis of a second preparation of the sample by the same microscopist. Thirteen samples were randomly selected for duplicate analysis.

The coefficient of variation for duplicate analyses was estimated by assuming a lognormal distribution for data on the original scale and estimating the variance on the log scale. For a random variable  $X$  with a lognormal distribution, the relationship between the coefficient of variation (CV) of  $X$  and the variance ( $\sigma^2$ ) of  $Y = \log_e X$  is given by

$$CV = [\exp(\sigma^2) - 1]^{\frac{1}{2}}$$

The variance was estimated by the error mean square obtained from a one-way ANOVA of  $\log_e$  concentration with sample ID as the experimental factor.

The error mean square for the ANOVA on the 13 duplicate QC samples is 0.066, which corresponds with an estimated coefficient of variation of 0.26. This compares with a coefficient of variation of 0.13 estimated in the precision study conducted during the design stage of the experiment. Because the precision study included only one carpet contamination level (100 million s/ft<sup>2</sup>) and no vacuuming treatment, a higher coefficient of variation for the experimental data is not unexpected.

Table 10 presents the results of the duplicate analyses.

TABLE 10. RESULTS OF DUPLICATE SAMPLE ANALYSES

Sample	Original		Duplicate	
	N	s/ft <sup>2</sup>	N	s/ft <sup>2</sup>
02-B017B	20	27,512,900	39	53,650,155
03-B026B	14	20,210,093	15	21,653,671
05-B051B	50	70,328,163	50	70,328,163
07-B073B	17	30,134,309	27	47,860,372
08-B090B	12	34,284,979	9	25,713,735
10-B110B	116	303,907,233	135	530,527,712
11-B125B	147	594,511,529	131	529,802,791
13-B147B	215	923,308,634	204	876,069,588
15-B171B	113	412,908,443	114	476,071,429
18B-1B	19	51,103,713	14	37,655,367
19B-1B	18	56,008,403	30	93,347,339
21B-2A	9	157,855,263	16	248,000,000
23B-1B	65	218,304,359	85	285,474,931

#### TEM ANALYSIS OF UNUSED SAMPLE CONTAINERS

Eleven unused, wide-mouth, polyethylene, screw-cap sample containers were analyzed for background asbestos contamination. Laboratory preparation was identical to that used for carpet samples, except no carpet segment was used. All 11 unused sample containers were found to be free of asbestos fiber contamination.

## SPRAY-APPLICATION TECHNIQUE

To confirm the validity of the spraying technique, an additional experiment was conducted with a pesticide sprayer identical to those used to apply the chrysotile to the carpet samples. An ampule of low-concentration suspension was diluted to 500 ml and then further diluted to 6 liters in the pesticide sprayer by using freshly distilled water. The sprayer was thoroughly shaken, and the contents were sprayed out into several containers. Three 500-ml samples of the spray were collected, one at the beginning of the spraying, one when approximately 50 percent of the contents had been discharged, and one just before the end of the spraying. These three samples were analyzed to establish that the concentration and size distribution of the fibers did not change during the spraying period. The results are presented in Table 11. These results indicate no significant loss of fibers during the transfer of the diluted liquid suspension through the sprayer's hose and nozzle.

TABLE 11. RESULTS FROM PRELIMINARY STUDY OF ASBESTOS DISPERSION BY SPRAYING--FIBERS AND FIBER BUNDLES (ALL LENGTHS)

Volume in sprayer at time of sample collection, liters	Fiber type	Structure concentration, 10 <sup>12</sup> structures/liter			Number of structures counted
		Mean	95% con- fidence interval	Analytical sensitivity	
6 (Beginning of spray)	Chrysotile	2.33	1.87-2.79	0.0118	198
4 (50% point of spray)	Chrysotile	2.18	1.54-2.82	0.0118	185
2 (End of spray)	Chrysotile	2.38	1.90-2.85	0.0118	202

The size distributions for these samples are listed in Table 12 and illustrated in Figure 6. Because the distributions are all approximate logarithmicnormal, the size range intervals for calculation of the distribution must be spaced logarithmically. Another requirement for the choice of size intervals is that they allow for a sufficient number of size classes while still retaining a statistically valid number of fibers in each class. Interpretation is also facilitated if each size class repeats at decade intervals. A ratio of 1.468 from one class to the next satisfies all of these requirements. The other constraint is that the length distribution should include the minimum fiber length of 0.5  $\mu$ m at the first interval point. The decade repeating automatically ensures that the other significant fiber length of 5  $\mu$ m occurs as an interval point.

No significant change in the fiber size distribution was evident during the transfer of the diluted liquid suspension.

TABLE 12. FIBER LENGTH DISTRIBUTIONS FROM THE PRELIMINARY STUDY OF  
ASBESTOS DISPERSION BY SPRAYING

Particle size range, $\mu\text{m}$	Number of fibers, fiber bundles (cumulative percentage)		
	Beginning of spray	50% point of spray	End of spray
0.23-0.34	0 (0)	0 (0)	0 (0)
0.34-0.50	0 (0)	0 (0)	0 (0)
0.50-0.73	28 (14.14)	33 (17.84)	24 (11.88)
0.73-1.08	48 (38.38)	55 (47.57)	43 (33.17)
1.08-1.58	34 (55.56)	28 (62.70)	45 (55.45)
1.58-2.32	30 (70.71)	20 (73.51)	28 (69.31)
2.32-3.41	34 (87.88)	17 (82.70)	22 (80.20)
3.41-5.00	18 (96.97)	14 (90.27)	19 (89.60)
5.00-7.34	4 (98.99)	10 (95.68)	13 (96.04)
7.34-10.77	1 (99.49)	5 (98.38)	5 (98.51)
10.77-15.81	1 (100.00)	3 (100.00)	1 (99.01)
15.81-23.21	0 (100.00)	0 (100.00)	1 (99.50)
23.21-34.06	0 (100.00)	0 (100.00)	0 (99.50)
34.06-50.00	0 (100.00)	0 (100.00)	1 (100.00)

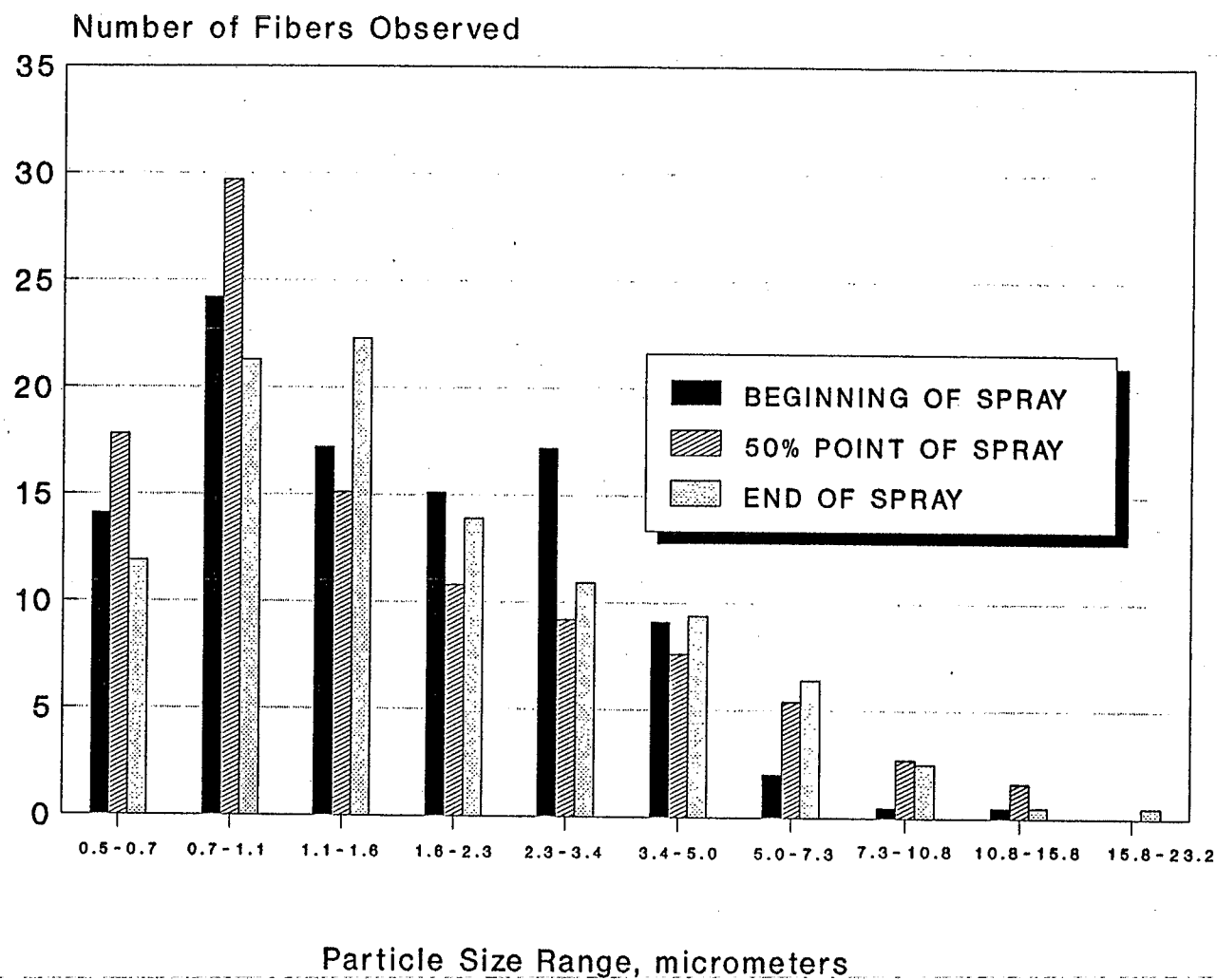


Figure 6. Fiber size distributions from preliminary study of asbestos dispersion by spraying.

## SECTION 7

### RESULTS AND DISCUSSION

#### CARPET SAMPLES

Figure 7 illustrates the average (geometric mean) concentrations of asbestos structures in the carpet before and after cleaning. The 95 percent confidence intervals for the geometric mean concentrations are given in Table 13. Individual estimates of carpet contamination are listed in Appendix C. For each experiment, a single estimated concentration was obtained before and after cleaning by taking the arithmetic mean of the three individual estimates. This gave 24 pairs of concentrations, one for each experiment. These estimates are presented in Appendix D.

TABLE 13. SUMMARY STATISTICS FOR ASBESTOS CONCENTRATIONS  
IN CARPET BEFORE AND AFTER CLEANING

Approximate contamination level, s/ft <sup>2</sup>	HEPA-filtered cleaner	Number of data points <sup>a</sup>	Geometric mean, million s/ft <sup>2</sup>	95 percent confidence interval
Before cleaning				
100 million	Hot-water extraction	6	62	(39, 101)
	Dry vacuum	6	47	(37, 59)
	After cleaning			
	Hot-water extraction	6	18	(8, 43)
	Dry vacuum	6	56	(38, 83)
Before cleaning				
1 billion	Hot-water extraction	6	589	(397, 873)
	Dry vacuum	6	535	(356, 803)
	After cleaning			
	Hot-water extraction	6	196	(85, 449)
	Dry vacuum	6	447	(240, 832)

<sup>a</sup> Each data point represents the average of three carpet samples.

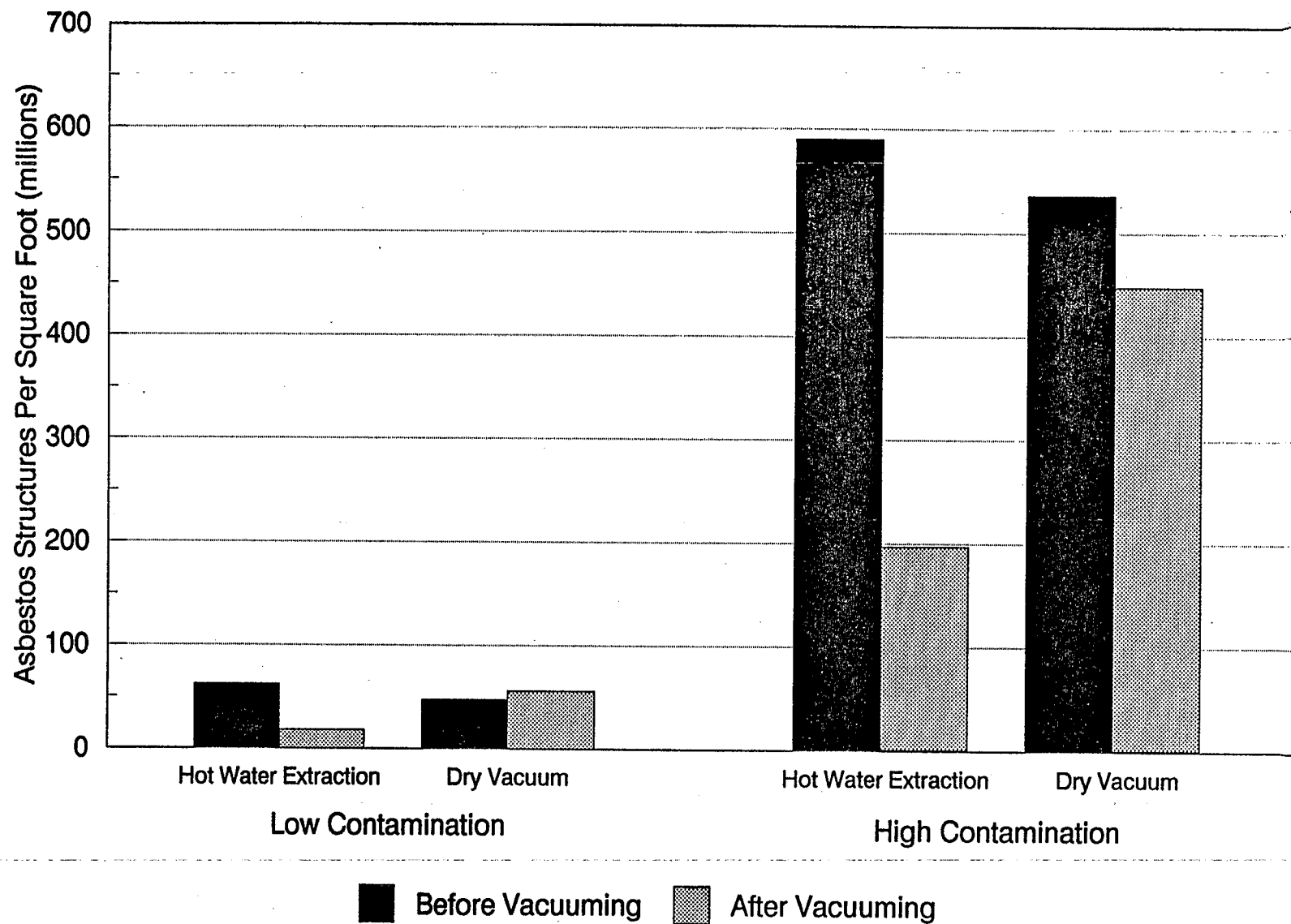


Figure 7. Average asbestos carpet concentrations before and after cleaning for each cleaning method and carpet contamination loading.

Results of a three-factor ANOVA indicated no significant difference between the results from Experiments 1 through 16 and Experiments 17 through 24 ( $p=0.7$ ). The difference between the two sets of experiments was that the carpet in Experiments 17 through 24 was first dry-vacuumed, then wet-cleaned, and then dry-vacuumed again prior to contamination. Because no significant difference was evident in the asbestos-retention characteristics of the new carpet versus new carpet that had first been wet-cleaned, the data from all 24 experiments were treated equivalently and reanalyzed by using a two-factor ANOVA.

Results of the two-factor ANOVA are presented in Table 14. The type of cleaning method had a significant effect ( $p<0.001$ ) on the difference between the asbestos concentrations before and after cleaning. The level of asbestos contamination in the carpet had no significant effect ( $p=0.622$ ). The estimated asbestos concentration in the carpet after cleaning, expressed as a proportion of the asbestos concentration before cleaning, is given in Table 15 and illustrated in Figure 8 together with 95 percent confidence intervals.

TABLE 14. ANALYSIS OF VARIANCE TABLE FOR DIFFERENCE BETWEEN ASBESTOS CONCENTRATIONS BEFORE AND AFTER CLEANING

Source of variation	Degrees of freedom	Sum of squares	F value	P value
Contamination level	1	0.074	0.251	0.622
Cleaning method	1	8.174	27.840	<0.001
Interaction	1	0.362	1.232	0.280
Error	20	5.872		

TABLE 15. ESTIMATED ASBESTOS CONCENTRATION IN CARPET AFTER CLEANING AS A PROPORTION OF THE CONCENTRATION BEFORE CLEANING

Contami- nation loading	HEPA-filtered vacuum	Concentration after cleaning as a pro- portion of concentra- tion before cleaning	95 percent confidence interval
Low	Hot-water extraction	0.29	(0.16, 0.51)
	Dry-vacuum	1.19	(0.68, 2.11)
High	Hot-water extraction	0.33	(0.19, 0.59)
	Dry-vacuum	0.84	(0.47, 1.48)

The asbestos concentration in the carpet after wet cleaning was approximately 0.3 of the asbestos concentration before cleaning in both the high and low contamination levels. The upper 95 percent confidence limit (Table 15) at each contamination level is less than 1, which indicates this is a statistically significant reduction.

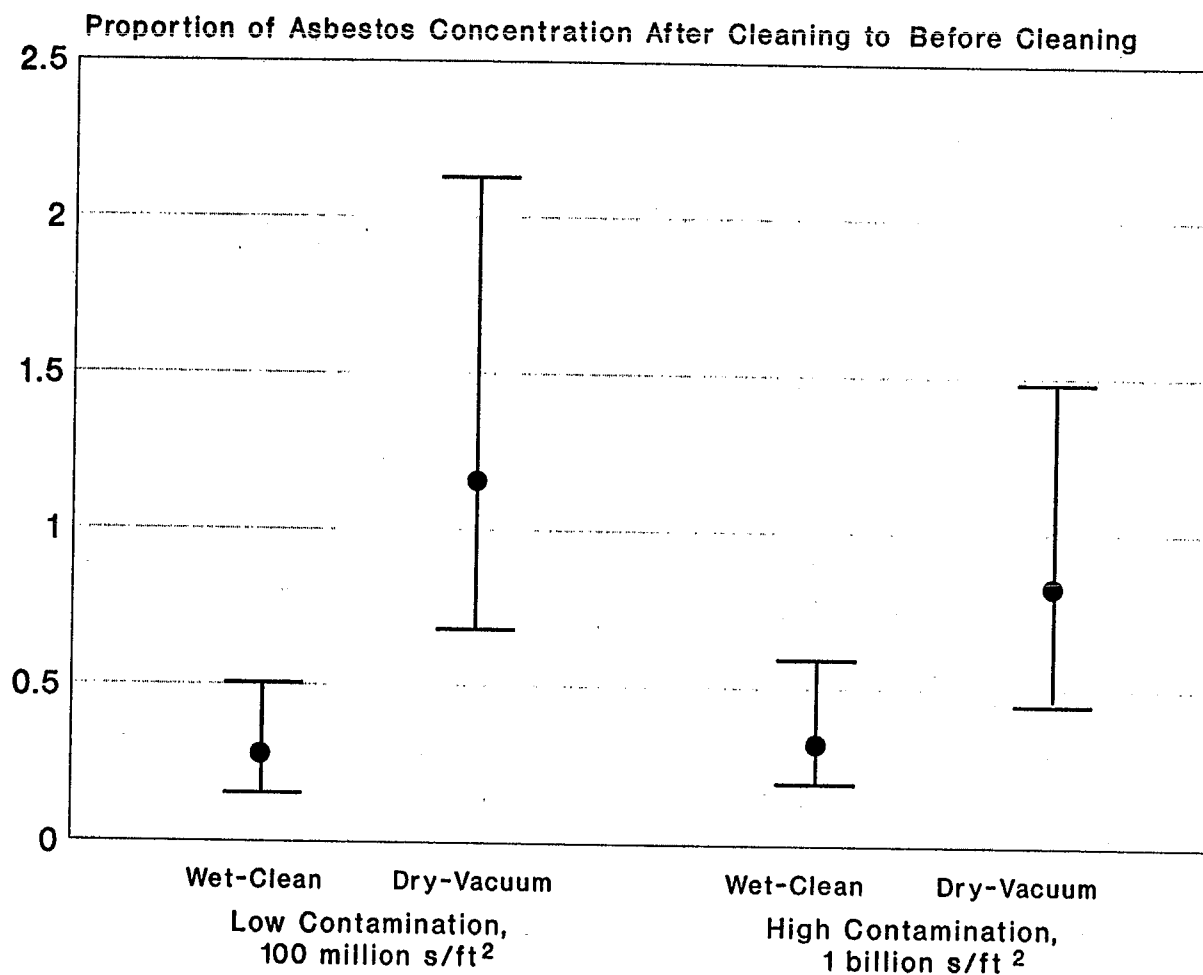


Figure 8. Ninety-five percent confidence intervals for the asbestos concentration after cleaning as a proportion of the concentration before cleaning.

The asbestos concentration in the carpet after dry-vacuuming was 1.2 times the concentration before cleaning for the low-contamination treatment and 0.8 times the concentration before vacuuming for the high-contamination treatment. The 95 percent confidence intervals for both estimates include 1, which indicates the data do not provide statistically significant evidence of either an increase or a decrease in asbestos concentration after dry vacuuming.

#### Asbestos Fiber Distributions in Carpet

The TEM analysis of the 144 carpet samples before and after cleaning yielded a total of 8101 asbestos structures. Of this total, 8080 (99.7%) were chrysotile and 21 (0.3%) were amphibole. The presence of amphibole asbestos fibers in the carpet was probably due to conditions existing prior to the study. Prestudy air monitoring identified two amphibole asbestos fibers in seven air samples collected. The structure morphology distribution for the particles in the carpet samples is summarized in Table 16.

TABLE 16. STRUCTURE MORPHOLOGY DISTRIBUTION IN CARPET SAMPLES COLLECTED BEFORE AND AFTER CARPET CLEANING

Structure type	Number of bundles	Number of clusters	Number of fibers	Number of matrices	Total
Chrysotile	1763	66	5893	358	8080
Amphibole	2	0	18	1	21
Total	1765	66	5911	359	8101

Appendix E presents the structure-length distributions of asbestos particles found in the carpet before and after cleaning. Figure 9 illustrates the cumulative percentage of fibers, for varying fiber lengths, observed 1) in the air during carpet cleaning activities, 2) in the carpet after dry-vacuuming and wet-cleaning, and 3) in the asbestos suspension used to contaminate the carpet. For carpet contaminated with 100 million s/ft<sup>2</sup>, a higher percentage of larger residual particles were consistently observed in the carpet after dry-vacuuming than after wet-cleaning. Fiber lengths of the residual asbestos in the carpet after dry-vacuuming and wet-cleaning carpet contaminated with 1 billion s/ft<sup>2</sup> were comparable. The reason for the difference in results between the two contamination levels is unknown.

#### AIR SAMPLES

Airborne asbestos concentrations were determined before and during carpet cleaning in Experiments 1 through 16 to study the effect of the cleaning method and contamination loading on fiber reentrainment during carpet cleaning. For each experiment, three work-area samples were collected before and

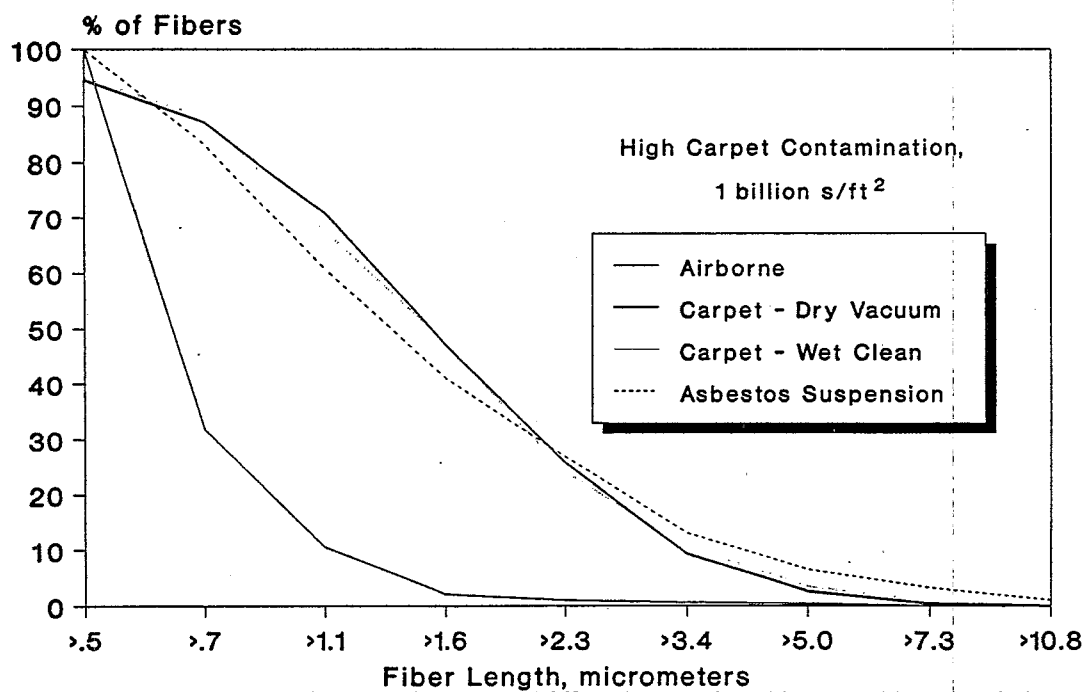
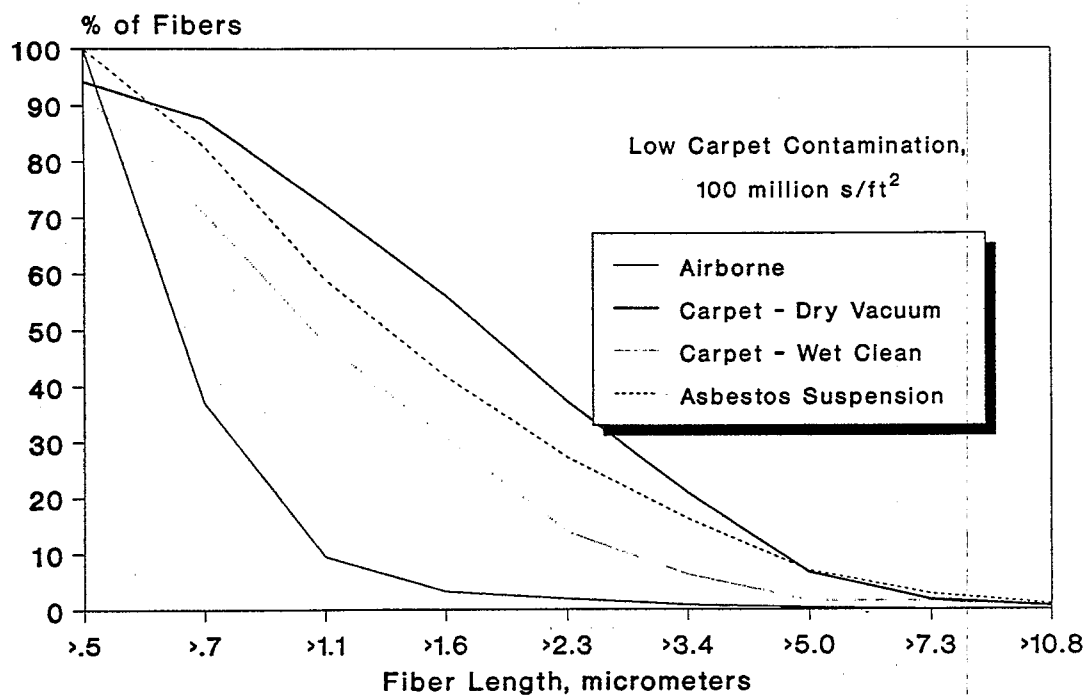


Figure 9. Cumulative percentages of asbestos particles in carpet after cleaning, airborne asbestos particles observed during cleaning, and asbestos fibers used to contaminate the carpet.

during the carpet cleaning. Figure 10 presents the average airborne asbestos concentrations measured before and during cleaning for each cleaning method and carpet contamination loading. The samples collected before cleaning were obtained after the carpet was contaminated to determine the baseline concentration in the test room.

The type of cleaning method had no significant effect ( $p=0.58$ ) on the difference between the airborne asbestos concentrations before and during cleaning. Similarly, the level of asbestos contamination in the carpet had no significant effect on fiber reentrainment ( $p=0.09$ ). Overall, however, the mean airborne asbestos concentration during carpet cleaning was significantly higher during carpet cleaning than just prior to cleaning ( $p<0.001$ ). A 95 percent confidence interval for the mean airborne asbestos concentration during carpet cleaning as a proportion of the airborne concentration before cleaning showed that the mean airborne asbestos concentration was between two and four times greater during carpet cleaning.

Figure 9 also illustrates that asbestos fibers in the air during carpet cleaning activities tended to be smaller in length than the asbestos fibers remaining in the carpet after cleaning. For example, overall approximately 17 percent of the asbestos fibers found in the carpet were less than  $1.0\text{ }\mu\text{m}$  in length; whereas approximately 85 percent of the fibers observed in the air were less than  $1.0\text{ }\mu\text{m}$ .

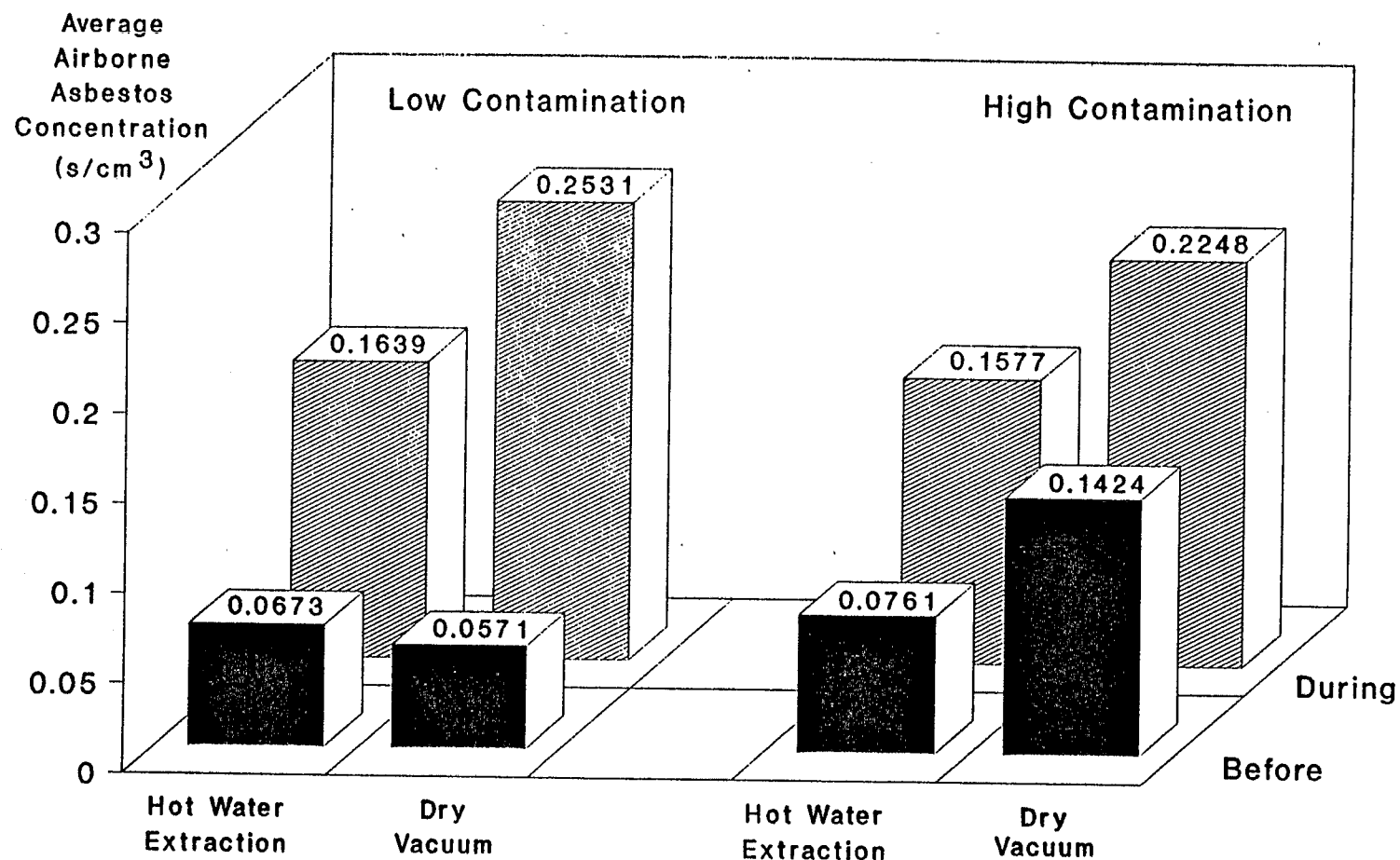


Figure 10. Average airborne asbestos concentrations before and during carpet cleaning.

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APPENDIX A

TRANSMISSION ELECTRON MICROSCOPY RESULTS FROM  
PRELIMINARY PERFORMANCE EXPERIMENTS ON  
THE MICROVAC AND SONIC EXTRACTION PROCEDURES

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Carpet Section	<u>Asbestos Structures</u>	
	Total Number	Per Square Foot

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SONIC EXTRACTION

E-1	109	$6.55 \times 10^8$
E-1	103	$8.26 \times 10^8$
E-1	104	$6.64 \times 10^8$
E-2	100	$4.78 \times 10^8$
E-2	106	$4.56 \times 10^8$
E-2	101	$4.28 \times 10^8$
E-3	117	$1.36 \times 10^9$
E-3	100	$1.16 \times 10^9$
E-3	107	$1.24 \times 10^9$
E-4	108	$6.41 \times 10^8$
E-4	100	$5.93 \times 10^8$
E-4	103	$4.89 \times 10^8$
E-5	119	$1.33 \times 10^9$
E-5	107	$9.57 \times 10^8$
E-5	104	$1.16 \times 10^9$
E-6	100	$5.42 \times 10^8$
E-6	100	$6.62 \times 10^8$
E-6	106	$6.53 \times 10^8$

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Carpet Section	<u>Asbestos Structures</u>	
	Total Number	Per Square Foot

MICROVAC

M-1	106	$3.41 \times 10^7$
M-1	33	$2.10 \times 10^7$
M-1	12	$1.52 \times 10^7$
M-2	11	$4.54 \times 10^6$
M-2	6	$2.48 \times 10^6$
M-3	9	$3.72 \times 10^6$
M-3	20	$8.26 \times 10^6$
M-3	24	$9.94 \times 10^6$
M-4	7	$2.89 \times 10^6$
M-4	5	$2.06 \times 10^6$
M-4	9	$3.72 \times 10^6$
M-5	114	$4.71 \times 10^7$
M-5	128	$1.06 \times 10^8$
M-5	92	$1.27 \times 10^8$
M-6	24	$9.94 \times 10^6$
M-6	23	$9.48 \times 10^6$

APPENDIX B

CHRYSOTILE FIBER SIZE DISTRIBUTION  
IN THE HIGH- AND LOW-CONCENTRATION AMPULES

# APPENDIX B

## CHRYSTILE FIBER SIZE DISTRIBUTION IN THE HIGH- AND LOW-CONCENTRATION AMPULES

TABLE B-1. FIBER LENGTH DISTRIBUTION IN THE  
LOW CONCENTRATION AMPULE

Particle size range, $\mu\text{m}$	Number of fibers counted	Cumulative fiber count	Percent of total	Cumulative percent
0.23 - 0.34	0	0	0.00	0.00
0.34 - 0.54	0	0	0.00	0.00
0.50 - 0.73	107	107	17.29	17.29
0.73 - 1.08	147	254	23.75	41.03
1.08 - 1.58	106	360	17.12	58.16
1.58 - 2.32	90	450	14.54	72.70
2.32 - 3.41	69	519	11.15	83.84
3.41 - 5.00	57	576	9.21	93.05
5.00 - 7.34	26	602	4.20	97.25
7.34 - 10.77	11	613	1.78	99.03
10.77 - 15.81	5	618	0.81	99.84
15.81 - 23.21	0	618	0.00	99.84
23.21 - 34.06	1	619	0.16	100.00
34.06 - 50.00	0	619	0.00	100.00
50.00 - 73.40	0	619	0.00	100.00
73.40 - 107.70	0	619	0.00	100.00
107.70 - 158.10	0	619	0.00	100.00
158.10 - 232.10	0	619	0.00	100.00
232.10 - 340.60	0	619	0.00	100.00

TABLE B-2. FIBER LENGTH DISTRIBUTION IN THE  
HIGH CONCENTRATION AMPULE

Particle size range, $\mu\text{m}$	Number of fibers counted	Cumulative fiber count	Percent of total	Cumulative percent
0.23 - 0.34	0	0	0.00	0.00
0.34 - 0.54	0	0	0.00	0.00
0.50 - 0.73	101	101	16.81	16.81
0.73 - 1.08	135	236	22.46	39.27
1.08 - 1.58	119	355	19.80	59.07
1.58 - 2.32	85	440	14.14	73.21
2.32 - 3.41	82	522	13.64	86.86
3.41 - 5.00	40	562	6.66	93.51
5.00 - 7.34	20	582	3.33	96.84
7.34 - 10.77	16	598	2.66	99.50
10.77 - 15.81	3	601	0.50	100.00
15.81 - 23.21	0	601	0.00	100.00
23.21 - 34.06	0	601	0.00	100.00
34.06 - 50.00	0	601	0.00	100.00
50.00 - 73.40	0	601	0.00	100.00
73.40 - 107.70	0	601	0.00	100.00
107.70 - 158.10	0	601	0.00	100.00
158.10 - 232.10	0	601	0.00	100.00
232.10 - 340.60	0	601	0.00	100.00

## APPENDIX C

### CARPET ASBESTOS CONCENTRATIONS BEFORE AND AFTER CARPET CLEANING

NOTE: Sample numbers ending with "B" indicate that the sample was taken before carpet cleaning; those ending with an "A" indicate that the sample was taken after carpet cleaning.

Sample Number	Number of Asbestos Str.	Asbestos Concentration, s/ft <sup>2</sup>
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EXPERIMENT 1 - WET CLEAN

01B-002B	43	53,830,766
01B-003B	36	46,213,405
01B-005B	46	48,257,407
01B-008A	3	41,311,983
01B-009A	6	7,835,031
01B-011A	22	28,482,906

EXPERIMENT 2 - DRY VACUUM

02B-014B	28	39,205,882
02B-016B	52	70,911,509
02B-017B	20	27,512,900
02B-020A	23	31,094,320
02B-021A	32	51,735,597
02B-023A	22	29,742,394

EXPERIMENT 3 - DRY VACUUM

03B-026B	14	20,210,093
03B-028B	33	49,823,310
03B-029B	25	35,641,711
03B-032A	40	58,254,124
03B-034A	26	41,541,412
03B-035A	6	9,058,784

EXPERIMENT 4 - WET CLEAN

04B-038B	26	38,897,868
04B-039B	46	72,789,649
04B-041B	46	66,992,243
04B-044A	2	29,921,437
04B-045A	4	65,827,160
04B-047A	3	49,370,370

Sample Number	Number of Asbestos Str.	Asbestos Concentration, s/ft <sup>2</sup>
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EXPERIMENT 5 - WET CLEAN

05B-050B	35	53,830,622
05B-051B	50	70,328,163
05B-053B	23	34,725,337
05B-056A	1	15,147,727
05B-057A	0	<15,147,727
05B-059A	0	<14,960,718

EXPERIMENT 6 - DRY VACUUM

06B-061B	34	54,323,385
06B-064B	17	24,005,297
06B-065B	28	44,014,151
06B-067A	107	215,793,694
06B-070A	7	11,435,049
06B-071A	32	47,607,143

EXPERIMENT 7 - DRY VACUUM

07B-073B	17	30,134,309
07B-075B	21	36,073,454
07B-078B	20	64,536,432
07B-079A	30	46,284,722
07B-081A	36	52,618,421
07B-084A	17	53,801,045

EXPERIMENT 8 - WET CLEAN

08B-086B	29	90,046,587
08B-088B	2	6,329,535
08B-090B	12	34,284,979
08B-092A	1	16,456,790
08B-094A	7	25,042,941
08B-096A	1	3,226,822

Sample Number	Number of Asbestos Str.	Asbestos Concentration, s/ft <sup>2</sup>
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EXPERIMENT 9 - WET CLEAN

09B-097B	140	577,413,366
09B-099B	129	497,560,764
09B-102B	104	393,215,339
09B-103A	5	75,738,636
09B-105A	3	45,443,182
09B-108A	3	51,269,231

EXPERIMENT 10 - DRY VACUUM

10B-110B	116	303,907,233
10B-111B	108	439,450,549
10B-113B	122	416,989,744
10B-116A	150	640,865,385
10B-117A	109	251,048,794
10B-119A	129	484,113,176

EXPERIMENT 11 - DRY VACUUM

11B-122B	118	232,134,002
11B-124B	127	384,752,273
11B-125B	147	594,511,529
11B-128A	39	464,169,643
11B-130A	22	33,630,734
11B-131A	1	16,021,635

EXPERIMENT 12 - WET CLEAN

12B-134B	103	416,562,500
12B-135B	125	425,063,776
12B-137B	145	732,140,152
12B-140A	41	152,491,629
12B-141A	106	379,833,333
12B-143A	120	393,602,362

Sample Number	Number of Asbestos Str.	Asbestos Concentration, s/ft <sup>2</sup>
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EXPERIMENT 13 - WET CLEAN

13B-146B	231	859,160,156
13B-147B	215	923,308,634
13B-150B	107	342,862,981
13B-152A	22	366,575,000
13B-153A	10	166,625,000
13B-156A	14	212,068,182

EXPERIMENT 14 - DRY VACUUM

14B-157B	116	315,825,163
14B-159B	107	441,308,787
14B-161B	25	416,562,500
14B-163A	113	362,088,942
14B-165A	104	451,276,042
14B-167A	99	196,379,464

EXPERIMENT 15 - DRY VACUUM

15B-171B	113	412,908,443
15B-172B	107	530,621,280
15B-173B	101	707,291,831
15B-177A	112	347,766,131
15B-178A	114	538,414,116
15B-179A	108	453,401,361

EXPERIMENT 16 - WET CLEAN

16B-182B	115	675,903,880
16B-183B	43	555,416,667
16B-185B	107	543,480,415
16B-188A	13	194,489,338
16B-189A	47	662,272,727
16B-191A	8	131,654,321

Sample Number	Number of Asbestos Str.	Asbestos Concentration, s/ft <sup>2</sup>
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EXPERIMENT 17 - WET CLEAN

17B-1B	2	31,738,095
17B-3B	19	56,889,039
17B-4B	25	79,345,238
17B-1A	0	<14,426,407
17B-3A	1	14,426,407
17B-4A	6	19,431,487

EXPERIMENT 18 - DRY VACUUM

18B-1B	19	51,103,713
18B-3B	15	49,590,774
18B-4B	28	85,448,718
18B-1A	28	76,609,195
18B-3A	18	53,894,879
18B-4A	27	77,902,597

EXPERIMENT 19 - WET CLEAN

19B-1B	18	56,008,403
19B-2B	83	292,695,767
19B-4B	41	114,145,781
19B-1A	1	2,601,483
19B-2A	1	17,632,275
19B-4A	6	79,345,238

EXPERIMENT 20 - DRY VACUUM

20B-1B	15	44,912,399
20B-3B	8	22,272,348
20B-4B	34	110,111,759
20B-1A	26	76,406,526
20B-3A	11	33,569,139
20B-4A	33	96,977,513

Sample Number	Number of Asbestos Str.	Asbestos Concentration, s/ft <sup>2</sup>
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EXPERIMENT 21 - WET CLEAN

21B-1B	102	894,513,158
21B-2B	223	1,499,490,517
21B-4B	128	860,694,108
21B-1A	23	403,407,895
21B-2A	9	157,855,263
21B-4A	51	674,434,524

EXPERIMENT 22 - DRY VACUUM

22B-1B	104	467,624,637
22B-2B	124	864,678,803
22B-3B	129	718,283,208
22B-1A	115	630,843,621
22B-2A	53	792,918,070
22B-3A	107	808,932,623

EXPERIMENT 23 - WET CLEAN

23B-1B	65	218,304,359
23B-2B	100	435,364,818
23B-4B	104	419,486,807
23B-1A	9	28,482,906
23B-2A	11	164,567,901
23B-4A	6	89,764,310

EXPERIMENT 24 - DRY VACUUM

24B-1B	137	1,142,809,762
24B-2B	86	251,509,434
24B-3B	202	1,649,914,216
24B-1A	75	1,306,862,745
24B-2A	110	321,698,113
24B-3A	69	1,082,082,353

APPENDIX D

AVERAGE ASBESTOS CONCENTRATIONS BEFORE  
AND AFTER CARPET CLEANING FOR EACH EXPERIMENT

Experiment	Cleaning Method	Contamination Level	Asbestos Concentration, s/ft <sup>2</sup>	
			Before	After
1	WET	LOW	49,433,859	25,876,640
2	DRY	LOW	45,876,764	37,524,104
3	DRY	LOW	35,225,038	36,284,773
4	WET	LOW	59,559,920	48,372,989
5	WET	LOW	52,961,374	5,049,242
6	DRY	LOW	40,780,944	91,611,962
7	DRY	LOW	43,581,398	50,901,396
8	WET	LOW	43,553,700	14,908,851
9	WET	HIGH	489,396,490	57,483,683
10	DRY	HIGH	386,782,509	458,675,785
11	DRY	HIGH	403,799,268	171,274,004
12	WET	HIGH	524,588,809	308,642,441
13	WET	HIGH	708,443,924	248,422,727
14	DRY	HIGH	391,232,150	336,581,483
15	DRY	HIGH	550,273,851	446,527,203
16	WET	HIGH	591,600,321	329,472,129
17	WET	LOW	55,990,791	11,285,965
18	DRY	LOW	62,047,735	69,468,890
19	WET	LOW	154,283,317	33,192,999
20	DRY	LOW	59,098,835	68,984,393
21	WET	HIGH	1,084,899,261	411,899,227
22	DRY	HIGH	683,528,883	744,231,438
23	WET	HIGH	357,718,661	94,271,706
24	DRY	HIGH	1,014,744,471	903,547,737

APPENDIX E

FIBER LENGTH DISTRIBUTIONS OF ASBESTOS  
IN CARPET SAMPLES COLLECTED BEFORE  
AND AFTER CARPET CLEANING

TABLE E-1. FIBER LENGTH DISTRIBUTION OBSERVED IN THE CARPET SAMPLES  
COLLECTED BEFORE CARPET CLEANING

Particle size range, $\mu\text{m}$	Number of fibers counted	Cumulative fiber count	Percent of total	Cumulative percent
0.23-0.34	18	18	0.3	0.3
0.34-0.54	78	96	1.5	1.8
0.50-0.73	165	261	3.1	4.9
0.73-1.08	404	665	7.5	12.4
1.08-1.58	875	1540	16.3	28.7
1.58-2.32	1150	2690	21.4	50.1
2.32-3.41	1149	3839	21.4	71.4
3.41-5.00	877	4716	16.3	87.8
5.00-7.34	439	5155	8.2	95.9
7.34-10.77	171	5326	3.2	99.1
10.77-15.81	42	5368	0.8	99.9
15.81-23.21	3	5371	0.1	100
23.21-34.06	1	5372	0	100
34.06-50.00	0	5372	0	100
50.00-73.40	1	5373	0	100
73.40-107.70	0	5373	0	100
107.70-158.10	0	5373	0	100
158.10-232.10	0	5373	0	100
232.10-340.60	0	5373	0	100

TABLE E-2. FIBER LENGTH DISTRIBUTION OBSERVED IN CARPET SAMPLES  
COLLECTED AFTER DRY VACUUMING OF CARPET CONTAMINATED WITH THE LOW  
CONCENTRATION DISPERSION

Particle size range, $\mu\text{m}$	Number of fibers counted	Cumulative fiber count	Percent of total	Cumulative percent
0.23-0.34	2	2	0.4	0.4
0.34-0.54	7	9	1.3	1.7
0.50-0.73	21	30	4.0	5.8
0.73-1.08	35	65	6.7	12.5
1.08-1.58	79	144	15.2	27.7
1.58-2.32	84	228	16.2	43.9
2.32-3.41	97	325	18.7	62.6
3.41-5.00	86	411	16.6	79.2
5.00-7.34	74	485	14.3	93.4
7.34-10.77	25	510	4.8	98.3
10.77-15.81	7	517	1.3	99.6
15.81-23.21	1	518	0.2	99.8
23.21-34.06	1	519	0.2	100
34.06-50.00	0	519	0	100
50.00-73.40	0	519	0	100
73.40-107.70	0	519	0	100
107.70-158.10	0	519	0	100
158.10-232.10	0	519	0	100
232.10-340.60	0	519	0	100

TABLE E-3. FIBER LENGTH DISTRIBUTION OBSERVED IN CARPET SAMPLES  
COLLECTED AFTER WET CLEANING OF CARPET CONTAMINATED WITH THE LOW  
CONCENTRATION DISPERSION

Particle size range, $\mu\text{m}$	Number of fibers counted	Cumulative fiber count	Percent of total	Cumulative percent
0.23-0.34	0	0	0	0
0.34-0.54	3	3	4.6	4.6
0.50-0.73	2	5	3.1	7.7
0.73-1.08	14	19	21.5	29.2
1.08-1.58	15	34	23.1	52.3
1.58-2.32	11	45	16.9	69.2
2.32-3.41	11	56	16.9	86.2
3.41-5.00	5	61	7.7	93.8
5.00-7.34	3	64	4.6	98.5
7.34-10.77	0	64	0	98.5
10.77-15.81	1	65	1.5	100
15.81-23.21	0	0	0	100
23.21-34.06	0	0	0	100
34.06-50.00	0	0	0	100
50.00-73.40	0	0	0	100
73.40-107.70	0	0	0	100
107.70-158.10	0	0	0	100
158.10-232.10	0	0	0	100
232.10-340.60	0	0	0	100

TABLE E-4. FIBER LENGTH DISTRIBUTION OBSERVED IN CARPET SAMPLES  
COLLECTED AFTER DRY VACUUMING OF CARPET CONTAMINATED WITH THE HIGH  
CONCENTRATION DISPERSION

Particle size range, $\mu\text{m}$	Number of fibers counted	Cumulative fiber count	Percent of total	Cumulative percent
0.23-0.34	4	4	0.2	0.2
0.34-0.54	23	27	1.4	1.7
0.50-0.73	60	87	3.7	5.4
0.73-1.08	123	210	7.6	12.9
1.08-1.58	262	472	16.1	29.1
1.58-2.32	389	861	24.0	53.0
2.32-3.41	346	1207	21.3	74.3
3.41-5.00	266	1473	16.4	90.7
5.00-7.34	108	1581	6.7	97.4
7.34-10.77	36	1617	2.2	99.6
10.77-15.81	7	1624	0.4	100
15.81-23.21	0	1624	0	100
23.21-34.06	0	1624	0	100
34.06-50.00	0	1624	0	100
50.00-73.40	0	1624	0	100
73.40-107.70	0	1624	0	100
107.70-158.10	0	1624	0	100
158.10-232.10	0	1624	0	100
232.10-340.60	0	1624	0	100

TABLE E-5. FIBER LENGTH DISTRIBUTION OBSERVED IN CARPET SAMPLES  
COLLECTED AFTER WET CLEANING OF CARPET CONTAMINATED WITH THE HIGH  
CONCENTRATION DISPERSION

Particle size range, $\mu\text{m}$	Number of fibers counted	Cumulative fiber count	Percent of total	Cumulative percent
0.23-0.34	0	0	0	0
0.34-0.54	4	4	0.8	0.8
0.50-0.73	21	25	4.2	5.0
0.73-1.08	35	60	7.0	12.0
1.08-1.58	101	161	20.2	32.3
1.58-2.32	102	263	20.4	52.7
2.32-3.41	116	379	23.2	76.0
3.41-5.00	67	446	13.4	89.4
5.00-7.34	36	482	7.2	96.6
7.34-10.77	13	495	2.6	99.2
10.77-15.81	4	499	0.8	100
15.81-23.21	0	499	0	100
23.21-34.06	0	499	0	100
34.06-50.00	0	499	0	100
50.00-73.40	0	499	0	100
73.40-107.70	0	499	0	100
107.70-158.10	0	499	0	100
158.10-232.10	0	499	0	100
232.10-340.60	0	499	0	100

**TECHNICAL REPORT DATA**  
(Please read Instructions on the reverse before completing)

1. REPORT NO.		2.		3. RECIPIENT'S ACCESSION NO.	
4. TITLE AND SUBTITLE Evaluation of Two Cleaning Methods for Removal of Asbestos Fibers From Carpet				5. REPORT DATE	
				6. PERFORMING ORGANIZATION CODE	
7. AUTHOR(S) John R. Kominsky, Ronald W. Freyberg, Jean Chesson				8. PERFORMING ORGANIZATION REPORT NO.	
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16. ABSTRACT  This research study examined the effectiveness of dry vacuuming and wet cleaning for the removal of asbestos fibers from carpet, and evaluated the potential for fiber reentrainment during carpet cleaning activities. Routine carpet cleaning operations using high-efficiency particulate absolute (HEPA) filtered dry vacuum cleaners and HEPA-filtered hot-water extraction cleaners were simulated on carpet artificially contaminated with asbestos fibers. Overall, wet cleaning the carpet with a hot-water extraction cleaner reduced the level of asbestos contamination by approximately 70 percent. There was no significant evidence of either an increase or a decrease in asbestos concentration after dry vacuuming. The level of asbestos contamination had no significant effect on the difference between the asbestos concentrations before and after cleaning. Airborne asbestos concentrations were two to four times greater during the carpet cleaning activities. The level of asbestos contamination in the carpet and the type of cleaning method used had no significant effect on the difference between the airborne asbestos concentration before and during cleaning.					
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